A COMPLETE SET OF SYSTEMS THINKING SKILLS

Article *in* Insight · September 2017

DOI: 10.1002/inst.12159

A Complete Set of Systems Thinking Skills

Ross D. Arnold
Stevens Institute of Technology
ross.arnold1@gmail.com

Jon P. Wade
Stevens Institute of Technology
jon.wade@stevens.edu

Abstract. This paper proposes a complete set of systems thinking skills for use across many different disciplines. The paper places particular emphasis on the ability to assess each of the skills quantitatively, a comprehensible description of the skills, and the completeness of the set. The proposed skills were derived from a review of the literature, the application of systems thinking experience, and the application of systems thinking to itself. Several different sets of systems thinking skills can be found throughout the systems community, but common key concepts can be distilled from these sets. When combinations of these concepts are considered separately, holistically, and together as a system, a single, cohesive set of skills emerges.

Systems thinking is widely believed to be of critical importance across many different fields; it has been said that skillful use of systems thinking skills could have prevented such disasters as World War II, the Great Depression, and the Challenger space shuttle disaster, as well as lessened or avoided the effects of many major environmental disasters. At the opposite send of the spectrum, systems thinking can be used to enhance health care, improve the economy, improve technology, laws, international and interpersonal relationships, schools, organizations, and so much more. However, this very useful skill set still lingers outside mainstream education. To address this problem, a set of assessable, comprehensible systems thinking skills is required. Such skills are defined, described, and detailed in this paper.

Background

The skills proposed in this paper are an extension of a definition of systems thinking proposed by Arnold and Wade (2015). Arnold and Wade define systems thinking as *a system 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 definition is backed by a thorough literature review as well as the System Test concept also proposed in the paper (Arnold and Wade 2015). The definition includes a Systemigram that describes the various interacting pieces of systems thinking. The Arnold and Wade definition, as well as the skills proposed in this paper, are part of a research effort to define, measure, and assess systems thinking. This effort supports a broader effort to expand the reach of systems thinking and systems engineering in general, including research using simulation as a way to accelerate learning in systems engineering (Zhang, Bodner, Turner, Arnold, & Wade, 2016).

The skills proposed in this paper will be used as the basis for the development of an assessment rubric to measure Systems Thinking Maturity, also sometimes called Systems Literacy (Plate and Monroe, 2010) or simply systems thinking skill. An assessment system will be derived from the skills and rubric, introduced to a set of thinkers, and tested for fidelity. As the proposed skills are described and organized in an assessable way, they are key to the success of the research objective: uncovering effective methods of systems thinking assessment, and, ultimately, delivering the vastly important concept of systems thinking to a broader audience.

Introduction

To those outside the systems community, the term *systems thinking* may feel complex or far-removed from reality. The truth, however, is quite the opposite. It is important to realize that systems, in this case, refer to all kinds systems. Interpersonal relationships, engineering projects, economies, school systems, organizations; these are all systems, and can all benefit from systems thinking. Systems thinking provides skills such as the ability to view issues holistically, and the insight to see non-obvious connections between things while understanding why they behave a certain way. These skills could apply equally as well to improving a relationship with one's children as they could to improving pedagogy techniques in impoverished communities (Luong & Arnold, 2016). It has even been claimed that the most threatening environmental disasters facing our planet could have been avoided or greatly lessened if systems thinking had been more prominent (Vallero & Letcher, 2013).

A critical step in assessing systems thinking is to identify the metrics and qualities that thinkers must master in order to improve their levels of Systems Thinking Maturity. However, systems thinking cannot be broken down to sub-elements, for it is an emergent outcome of the skills that support it. The act of reduction is to defeat its essence as a system. The mental model for the identification of systems thinking skills should be to identify skills that support systems thinking ability, rather than the skills that systems thinking is "made up of." Systems thinking is its own system, and there are also skills that support it. Systems thinking cannot be regarded as, simply, the skills that support it. When examining systems thinking as a system by considering both the forest and the trees (Richmond, 1993) and seeing both the whole and the parts (Hatfield, 2011), it becomes clear that both the individual concepts and systems thinking as a whole are key to its assessment.

A systems thinker must use an understanding of the way a system's agents interact in order to generate a theory of behavior. In the same way, we must use an understanding of the proposed systems thinking concepts, and the way they interact with each other, to assess Systems Thinking Maturity. Ultimately we must take a Systems Approach to measuring Systems Thinking Maturity, and celebrate the similarities between skills rather than the differences (Richmond, 1993).

Problem

All systems are "made up of stuff" and the way that that "stuff "is expressed and organized depends on the context in which it is used. When we describe systems thinking, we express its "stuff" in a particular way to facilitate assessment and education. As a first step in this approach, concepts of systems thinking described in the literature were examined. Some of these include wholes and parts, dynamic behavior, conceptual modeling to simplify systems, feedback loops, delays, synergy, multiple perspectives, and uncertainty, among others (Arnold & Wade, 2015; Bonnema, 2012; Ossimitz, 2000; Plate, 2010; Richmond, 1994; Stave & Hopper, 2007; Sweeney & Sterman, 2000).

But what must a person actually do in order to demonstrate looking at both wholes and parts, or understanding dynamic behavior? The practical applications of systems thinking to the real world must be determined. From there, the skills a person must perform in order to be using systems thinking must be identified. Those abilities can then be mapped to the theoretical concepts above. This approach is analogous to determining Student Learning Objectives (SLOs) in the education field, or determining Acceptance Criteria in the software engineering field.

There is a gray area in which the systems thinking skills match up with the theoretical concepts; this area is likely to be open to some amount of interpretation. Such limitations are inherent in many fields, especially when taking practical applications and mapping them to educational constructs (Cuevas, Matveev, & Miller, 2010). However, in order to evaluate quantitatively in an education system, we must take the bottom-up approach of defining and mapping the theory to a taxonomy. But, in order to actually evaluate realistically relevant skills, we must take the top-down approach of determining the real actions that people take and then mapping those to some form of objectives. The area in which the "rubber meets the road" between these two approaches is likely to remain somewhat ill-defined; however, as long as this research proves that it is possible to apply various methods to evaluate practical systems thinking skills, the research goals are accomplished. Taking a systems approach to a problem reveals that there is no such thing as a complete theory; the quest is to look at a problem more comprehensively, and the resolutions come from rethinking how we deal with complexity (P. Senge, 1990) and with it, systems thinking.

Two Facets of Systems Thinking

When identifying systems thinking competencies it is important to point out that the boundary of the *system* of systems thinking extends further than simply *systems understanding*. Systems thinking can be regarded as encompassing two distinct facets, or areas of skill:

- **Gaining Insight**: Improving systemic insight of a particular system
- **Using Insight**: Applying systemic insight to a particular system

These are two very different sets of techniques. Systems thinking includes both the ability to gain systemic insight, and the ability to use that insight to understand and affect systems. To ignore one of these areas or to fail to recognize their distinction from each other is to invite partial understanding of systems thinking.

Gaining insight roughly equates to approaching systems from the outside, such as examining a system from multiple perspectives. This includes techniques for effectively understanding system behavior even in the face of lacking specific understanding of all the details on how the system works (Wade & Heydari, 2014). What does a person do when she can't understand all the details of a systems operation, and what are her techniques for trying to understand its behavior?

Using insight roughly equates to approaching systems from the inside, such as manipulating system structure. This encompasses the understanding of systems, system structure, and dynamic behavior, all widely considered highly relevant aspects of systems thinking (Hopper & Stave, 2008; Richmond, 1993; Squires, Wade, Dominick, & Gelosh, 2011; Stave & Hopper, 2007; Sterman, 2003).

These two sets of techniques are used both in parallel and in series, constantly reinforcing each other while a thinker explores a system of interest (Fig. 1).

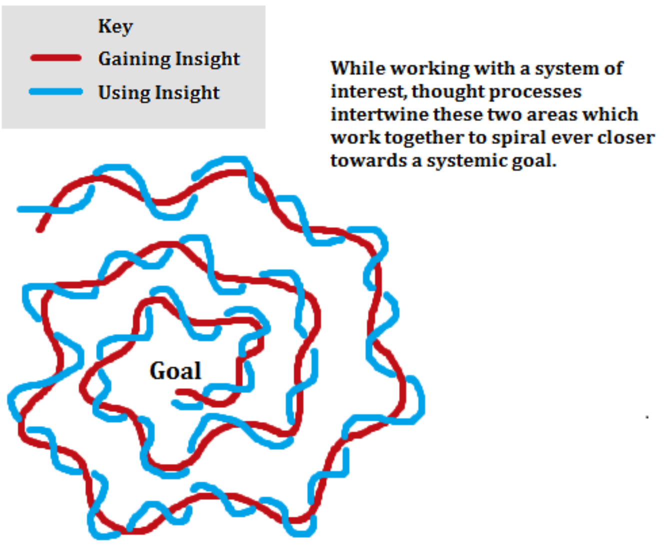

Figure 1. The Systems Thinking Spiral: gaining and using insight

Skills that Support Systems Thinking

This section proposes a set of skills that support systems thinking. These skills support the four basic principles of systems thinking as per the Arnold and Wade (2015) definition:

1. Identifying Systems
2. Understanding Systems
3. Predicting System Behavior
4. Devising Modifications to Systems to Produce Desired Effects[1]

There are many valid ways to organize and ponder the skills that support systems thinking. This paper proposes dividing the skills into four basic domains. Some models have broken out systems thinking into even more skills. However, in the interest of taking a systems approach and avoiding reductionism, the skill model for this research has been deliberately synthesized and simplified using a holistic perspective. In each of the domains, keeping the wholes and parts both in mind, several sub-skills have been separated out. The combination of skills in these four categories covers a large majority of the skills and domains sought to be measured according to the literature and is the most appropriate way to approach skill measurement for this research. The domains and their skills are:

1. **Mindset** – *How to approach systemic problems*
   1.1. Explore Multiple Perspectives
   1.2. Consider the Wholes and Parts
   1.3. Effectively Respond to Uncertainty and Ambiguity
   1.4. Consider Issues Appropriately
   1.5. Use Mental Modeling and Abstraction
2. **Content** – *What's in the system*
   2.1. Recognize Systems
   2.2. Maintain Boundaries
   2.3. Differentiate and Quantify Elements
3. **Structure** – *How's it organized*
   3.1. Identify Relationships
   3.2. Characterize Relationships
   3.3. Identify Feedback Loops
   3.4. Characterize Feedback Loops
4. **Behavior** – *What happens when content and structure interact*
   4.1. Describe Past System Behavior
   4.2. Predict Future System Behavior
   4.3. Respond to Changes over Time
   4.4. Use Leverage Points to Produce Effects

A sample line of reasoning along the lines of these domains might be: *How do I learn about systems (Mindset)? Does this thing belong in the system (Content)? How is this thing related to other things (Structure)? What's happening when these things interact, and how can I make it do what I want (Behavior)? Now how do I discover more about this system (Mindset)?*

Systems thinking is often associated with a variety of cognitive personality traits. Although that line of research is fascinating, this research focuses on the actual construct of systems thinking, not the cognitive traits commonly associated with successful systems thinkers. This research focuses on identifying and quantifying what systems thinking *actually is*, rather than the mental traits correlated with its development and use by thinkers (for example, "open-minded-ness").

---

[1] Implicit in this 4th principle is also the concept that a systems thinker must determine if a modification has produced the desired result.

Mindset Domain

How do we approach systems and systemic problems?

This foundational, yet highest-order set of systems thinking skills is simultaneously a mindset that precedes all other systems work, a philosophical set of principles that accompany all systems thinking activities, and a set of paradoxical feedback loops that enable effective systems thinking. This may sound complex, but the key point is that the effective use of these skills results in a mindset, and tends to manifest as problem-solving philosophy. The paradoxical nature of some of these principles implies an ability to juggle two opposing facets of a phenomenon and, rather than become confused or frustrated by this opposition, recognize and use the inherent truths of each facet to advantage.

The *Mindset* skills tend to mature and develop over time as a set of higher order emergent skills which encompass and enhance all systems work. Despite their higher order nature the Mindset skills are probably also the first that should be taught to a systems thinker, and thus they are listed first in this skill set. A thinker may not need insight into a particular system to use these skills; these are *Gaining Insight* skills and represent some of the special ways that a systems thinker develops and enhances systemic insight.

Skill 1.1 Explore Multiple Perspectives				
Low Maturity	→	→	→	High Maturity
Approaches a system from only one perspective	Explores other familiar perspectives when approaching a system	Begins to explore unfamiliar or contentious perspectives	Actively explores unfamiliar perspectives, but still tends to miss some non-obvious perspectives	Actively explores multiple, non-obvious perspectives, some of which might conflict with the thinker's view

A systems thinker investigates a problem by objectively examining multiple subjective perspectives (Richmond, 1993; Waters & Waters, 2014). A thinker needs to look at a problem from many different perspectives and in many different ways. Some of these ways might be non-obvious, unfamiliar, or even distressing, especially if they conflict with a thinker's own world-view.

Skill 1.2 Consider the Wholes and Parts				
Low Maturity	→	→	→	High Maturity
Does not consider the system holistically	Considers some holistic aspects of systems but misses others; tends to spend too much time in particular areas	Considers the system holistically but tends to miss the importance of the parts; occasionally gets stuck in an event	Tends to consider the system holistically and considers the importance of the parts in most cases	Considers both the "forest" and the "trees" keeping "one eye on each" consistently while approaching systems

A systems thinker considers both the "forest and the trees" (Richmond, 1994). An appreciation for both the wholes and parts, simultaneously, is a critical systems thinking skill (Richmond, 1993; P. Senge, 1990; Stave & Hopper, 2007).

Skill 1.3 Effectively Respond to Uncertainty and Ambiguity				
Low Maturity	→	→	→	High Maturity
Stops when faced with uncertainty or ambiguity	Difficulty making decisions during uncertain times or in ambiguous circumstances	Decisions made when faced with uncertainty are as often flawed as are appropriate	Decisions made when faced with uncertainty are often appropriate	Able to make sustainable system decisions despite uncertainties in their outcomes

Initially, it may be difficult to determine the best solution to a systemic problem, if one even exists. When dealing with systems, uncertainty and ambiguity are often present. However, a systems thinker should be able to make decisions that guide a system towards a desired state (Burandt, 2011). A systems thinker needs to have the ability to move forward while analyzing or designing a system, despite the uncertainty inherent in any complex system. An ability to effectively respond to this ambiguity without simply stopping work, becoming stuck, or making inappropriate decisions is an important systems thinking skill.

One way to effectively respond to uncertainty is through successive approximation (Waters & Waters, 2014). Using successive approximation, a systems thinker may try a solution and then assess the results in cycles, moving closer to a systemic goal with each successive trial. This skill supports many other skills, such as investigating relationships (especially unknown ones) and the productive inquisition that is core to systems thinking.

Skill 1.4 Consider Issues Appropriately				
Low Maturity	→			High Maturity
Takes a reactionary approach to issues	Takes a reactionary approach to issues, but tends to realize that this approach has flaws	Sometimes takes appropriate time to allow issues and complexities to emerge; still reacts to issues / jumps to conclusions sometimes	Rarely jumps to conclusions when issues occur; often spends appropriate time to absorb complexity	Allows time for the complexity of a situation to sink in; rarely, if ever, jumps to conclusions; almost always considers issues appropriately

An experienced systems thinker takes time to absorb the complexity of a situation rather than reacting immediately to (even stressful) stimuli (Waters & Waters, 2014). Considering issues appropriately is a key part of the systems thinking mindset. The ability to determine what "appropriate" means for a given system is also part of this skill.

Skill 1.5 Use Mental Modeling and Abstraction				
Low Maturity	→			High Maturity
Does not recognize the value of mental modeling; intuitive models are highly inaccurate, overly simple, or overly complex	Recognizes the benefit of simplification through mental modeling; mental models may be inaccurate, overly simple, or overly complex	Recognizes that different mental models can influence perspectives and actions differently; able to simplify the problem through mental modeling with some accuracy and simplicity	Able to simplify the problem through mental modeling with increasingly accurate results using increasingly simpler models; recognizes that all models are flawed but some are useful	Devises the simplest mental model that accurately describes the system for a given purpose; recognizes that all models are flawed but some are useful

It is not possible to fit all of reality into our minds; therefore, we *model* various aspects of reality (Richmond, 2004). Our mental models are simplified abstractions of parts of reality used to make meaning out of what we're experiencing. Systems thinkers mentally model systems and parts of systems as a way to simplify and understand structure and behavior. These models are fluid and constantly updated, and often support the ability to communicate complex systemic nature in simpler, more approachable ways. Systems thinkers also use mental models to create and test assumptions mentally via thought experimentation.

Part of the mental modeling skill is the appreciation for the different types of mental models and how they can affect human behavior in systems (Waters & Waters, 2014). For example, two thinkers investigating the same phenomenon but approaching it with two different mental models may arrive at different conclusions. Both sets of conclusions may well be valid, and may include useful details excluded in the other. An appreciation for the different types of models reinforces the *Exploring Multiple Perspectives* skill.

Content Domain

What is the system, what's inside it, and what's outside it?

A systems thinker performs a variety of activities while resolving systemic problems. These activities begin with the recognition of a behavior of interest and its associated system or systems (International Council on Systems Engineering, 2014). The importance of choosing appropriate boundaries in systems is widely recognized (Boardman, Sauser, John, & Edson, 2009; Frank, 2012; Valerdi, 2012). Identifying the elements within a particular system (its contents) is, in fact, defining its boundary.

Consider system boundaries in the context of quantum physics. Systemic elements have conceptual similarities to electron density in atoms. Elements and relationships in a system can be thought of as having probabilities of relevance. The closer an element is to the most important components of the system, the higher the probability that it should be included in a particular system of interest. Outside of the obvious components lies a large *gray area* in which the probabilities of relevance fall off drastically, beyond which lies the "rest of the world" – items that exhibit very low probabilities of relevance and thus are generally not appropriate for inclusion in the boundary of the system. This concept can be thought of as System Boundary Density. Similar to the idea that electron density is the measure of the probability of an electron being present at a specific location in an atom: *System Boundary Density is the measure of the probability that an element is relevant to a system in a particular context and/or at a particular time*.

This concept may be one of the root causes of difficulty in defining system boundaries; the boundaries themselves are often ill-defined and not as clear as might be desired. They have a tendency to change as the context and problem-at-hand changes (Wade & Heydari, 2014). A skilled systems thinker will recognize the System Boundary Density of particular elements, and pick the appropriate elements out from the gray area for inclusion in the system of interest. An inexperienced systems thinker might extend the gray area too far (including irrelevant or extraneous items) or not far enough (failing to include key elements and interactions).

Understanding how and why systemic boundaries are difficult to define helps to determine how this skill might be demonstrated and evaluated in a research scenario.

Skill 2.1 Recognize Systems				
Low Maturity →				High Maturity
Does not recognize that a problem is systemic	Recognizes that the problem is systemic but cannot identify it	Recognizes that the problem is systemic and is able to identify associated behavior or system of interest in general terms	Recognizes that the problem is systemic and is able to identify associated behaviors or systems of interest increasingly more concrete terms	Recognizes that the problem is systemic and is able to identify associated behaviors or systems in concrete terms

Recognizing that a particular problem is systemic in nature is often considered the first step when exercising systems thinking (International Council on Systems Engineering, 2014). At this point, the thinker has not yet defined the boundaries of the system, but has recognized that such a construct exists and may have a conceptual idea of its contents.

Skill 2.2 Maintain Boundaries				
Low Maturity →				High Maturity
Unable to define the boundary of a system	Able to create an initial mental model of the system that contains some relevant elements. May contain extraneous elements or miss key elements	Able to maintain a system boundary that, over time and context, contains most of the relevant elements and minimizes extraneous elements	Able to maintain a system boundary of the system over time with increasing accuracy	Able to maintain an accurate boundary of the system that correctly changes over time and context with a high degree of quantitative accuracy

The boundary defines the content of the system. Maintaining that boundary is a key systems thinking skill (Boardman et al., 2009; Frank, 2012; Valerdi, 2012). *Maintain* is key word here, as it indicates that this skill is continuously applied. The boundary is not defined once and then forgotten; rather, it is continuously maintained and updated over time and with changing system contexts. This boundary is maintained as a mental model.

Skill 2.3 Differentiate and Quantify Elements				
Low Maturity →				High Maturity
Unable to recognize that elements are different	Able to identify and differentiate between stocks and flows, as well as other types of variables and elements	Able to estimate properties of elements, such as the maximum quantity of a stock or the rate of a flow	Able to quantify properties of elements, such as the maximum quantity of a stock or the rate of a flow with increasing accuracy	Able to describe the properties of elements with a high degree of accuracy

Understanding and differentiating between the elements in a system, such as their properties, types, and natures, are critical to understanding systems (Plate & Monroe, 2014; Stave & Hopper, 2007). Differentiating types of stocks, flows, and variables as described by Plate and Monroe (2014) and Stave and Hopper (2007) is a part of this skill. In this case, stock refers to any storage or resource pool within the system. Stocks could range from physical, like the amount of water in a bathtub, to abstract, like the trust level in a relationship between two people. Flows are changes to stocks, such as information flows, energy or material flows, or even decision-making flows. However, this skill extends beyond just stocks and flows, to the nature and properties of other elements in the system. For example, these elements and variables could include particles, pressure and temperature (for ideal gases) or culture and opinions in human systems.

Structure Domain

How is the content of the system organized?

Structure is the way that something is organized (Merriam-Webster 2016). It can also be described as the arrangement of and relations between the parts or elements of something complex (Oxford Dictionary, 2016). System structure, therefore, is the way the system is organized. It is the way that the parts of the system relate to each other. Recognizing and understanding these relationships, often called interconnections, is core to systems thinking (Richmond, 1993; Stave & Hopper, 2007; Sterman, 2003). However, even highly educated adults without systems thinking training tend to lack skill in this ability (Plate & Monroe, 2014). Systems thinkers investigate a system by exploring its many connections, parsing out the important from the unimportant while determining the properties of the connections themselves. While the systems thinker explores these relationships, an understanding of system structure emerges. More complex systems thinking skills build upon the ability to understand relationships and, by extension, system structure.

In many cases, recognizing a relationship between elements actually reveals additional system content. Structure and content skills are performed together in an iterative fashion. Structure skills seek to connect content, while also revealing gaps in content. Content skills reveal gaps in structure. As connections are explored and the structure is revealed, the connections that "point into the unknown" reveal additional parts of the content.

Relationship recognition skills actually have two distinct dimensions. Identification is the first, and the second is the ability to grasp a relationship's strength and properties; also known as characterization. There is a difference between seeing relationships, and understanding how they work. The characterization could be qualitative, such as through estimation, or quantitative, as through precise mathematical modeling. Characterization also implies the ability to understand the connection. A thinker could recognize many connections without necessarily understanding them, or understand some connections very well while failing to recognize many others.

Skill 3.1 Identify Relationships		
Low Maturity	→	High Maturity
Unable to recognize even those relationships that would be considered obvious by novice systems thinkers	Increasing ability to recognize relationships that are distant or complex in space, time, or other factors; larger volume of relationships recognized	Able to recognize the vast majority of relevant relationships, even obscure, meta-physical, non-obvious, or complex ones

Recognizing that two parts of a system are related in some way is a basic systems thinking skill (P. M. Senge, Kleiner, Roberts, Ross, & Smith, 1994; Squires et al., 2011; Stave & Hopper, 2007). Relationships are often called interconnections, or just connections. Increasing levels of maturity in this skill are demonstrated by the ability to recognize increasingly non-obvious, more complex and less visible connections.

Skill 3.2 Characterize Relationships				
Low Maturity	→			High Maturity
Unable to characterize the strength of a relationship	Unable to characterize the strength of a relationship with accuracy or consistency	Able to estimate the strength of a relationship with some consistency	Able to characterize relationships with increasing accuracy	Able to create highly accurate characterizations of relationships

Characterizing relationships demonstrates an understanding of how two things are related. Characterizing, in this case, can be defined as describing the distinctive nature or features of a relationship. Increasing levels of maturity result in an increasingly clear and accurate picture of how a relationship works, what its characteristics are, and how strong it is.

Skill 3.3 Identify Feedback Loops		
Low Maturity	→	High Maturity
Unable to recognize feedback loops	Increasing ability to recognize non-linear feedback loops (loops that are distant in space, time, or other factors); larger volume of feedback loops recognized	Able to recognize the vast majority of relevant feedback loops

Relationships can form feedback loops. Although similar, and possibly an extension of the identification of relationships, the identification of feedback loops likely requires additional systems skill. This skill is potentially different than just recognizing that relationships exist or recognizing their strengths; this is recognizing that something different has occurred or is occurring here; something emergent.

Skill 3.4 Characterize Feedback Loops				
Low Maturity	→	→	→	High Maturity
Unable to characterize the strength and properties of a feedback loops	Unable to characterize feedback loops with accuracy or consistency	Able to estimate the strength and properties of feedback loops with some consistency	Able to characterize feedback loops with increasing accuracy	Able to create highly accurate characterizations of feedback loops

Feedback loops must also be characterized in terms of their strengths and properties (reinforcing vs. balancing, as well as delays and other temporal properties). As with interconnections, characterization in this case does not necessarily imply a precise quantity. The characterization may start as a highly qualitative estimate of the various features and strengths of a feedback loop, but will become more precise as a thinker's Systems Thinking Maturity increases. As with relationships, it may be possible to characterize several feedback loops with a high degree of accuracy, but yet fail to detect a large number of the relevant feedback loops present in a system.

Characterizing feedback loops also involves the ability to recognize and understand delays. Recognizing and understanding delays is an important system skill (Sweeney & Sterman, 2000), and the ability to understand and quantify them may be an indicator of Systems Thinking Maturity (Ossimitz, 2002).

Behavior Domain

How do the organization, elements, their properties, and other factors interact to produce behavior? What can we do to change that behavior?

Interconnections, the way they combine into feedback loops, and the way these feedback loops influence and consist of stocks, flows, and variables create dynamic behavior within a system (Arnold & Wade, 2015). This behavior can be difficult to grasp without systems training (Plate & Monroe, 2014). However, understanding dynamic behavior is a key systems thinking skill (Stave & Hopper, 2007; Sweeney & Sterman, 2000).

Skill 4.1 Describe Past System Behavior				
Low Maturity	→	→	→	High Maturity
Unable to describe past behavior	Able to describe past system behavior in general, conceptual terms	Able to describe past system behavior through estimation	Able to describe past system behavior with increasing levels of accuracy	Able to describe past system behavior with a high degree of accuracy

Describing past system behavior requires an understanding of how the system has worked in the past. This ties to the Arnold and Wade (2015) definition of systems thinking, in which understanding and describing system behavior is critical. Past system behavior refers not only to holistic system behavior but also to behavior of specific parts of the system at specific points in time. This skill emerges as a combination of all of the Content and Structure skills.

Skill 4.2 Predict Future System Behavior				
Low Maturity	→	→	→	High Maturity
Unable to predict future behavior	Able to predict future system behavior in general, conceptual terms over short timescales	Able to predict future system behavior in estimated terms over short timescales	Able to predict future system behavior with increasing levels of accuracy over longer timescales	Able to predict future behavior with a high degree of accuracy over a long timescale

Predicting future behavior is often more difficult than describing past behavior. As with the *Describe Past System Behavior* skill, the *Predict Future System Behavior* skill emerges as a combination of all

Content and Structure skills. However, future behavior prediction also requires an appreciation for the way systems change over time and the way dynamic behavior manifests itself. This includes an ability to recognize epochs of operation after which a system might change in substantial ways.

Skill 4.3 Respond to Changes over Time				
Low Maturity	→	→	→	High Maturity
Does not respond differently to changes in the system over time	Recognizes the need to respond differently over time	Responds to changes over time in ways that are occasionally effective	Responds to changes over time in increasingly effective ways	Consistently responds to changes over time in highly effective ways

A key systems thinking skill is the ability to effectively respond to changes in a system over time (Waters & Waters, 2014), rather than treating a system as an unchanging entity. If an effective strategy is discovered, it can be easy to continue to apply the same strategy to a system repeatedly. However, systems can change in significant, strategy-breaking ways. A systems thinker needs to continuously evaluate whether a given strategy is still valid, or whether system behavior has become fundamentally different due changes that have occurred over time.

Fundamentally, this skill is about the ability to re-evaluate one's own strategy without falling into a "comfort zone." A thinker skilled in the Content and Structure domains may indeed devise an effective system-handling strategy at a given time, but does the thinker also possess the wisdom to re-evaluate the strategy when it becomes obsolete?

Skill 4.4 Use Leverage Points to Produce Effects				
Low Maturity	→	→	→	High Maturity
Does not recognize leverage points in a system	Recognizes obvious or lower strength leverage points, but often pushes them in the wrong direction	Recognizes some high strength leverage points, and usually pushes them in the right direction	Recognizes most low and high strength leverage points, understands their differences, and uses them effectively most of the time.	Recognizes points of high leverage in a system. Consistently uses those leverage points to influence system behavior in desired ways.

Ultimately, it is not enough to simply understand a system and describe its behavior. A systems thinker must to be able to change a system to make it perform in desired ways (Arnold & Wade, 2015). These changes always depend upon the system and context, but there are a set of commonly recognized leverage points in which to intervene in a system (Meadows, 2008). These leverage points include different types of flows and feedback loops, high strength connections such as information flows and goals, the ability to self-organize, and the paradigms or mindsets from a which a system is born. A systems thinker is able to recognize the key leverage points in a system and push these points in the right direction to influence system behavior. As the final skill in the proposed skill set, this is the application of systemic knowledge and is critically important to successful systems work.

Skill Mapping

Are these the skills that the systems community is looking for?

Table 1 maps the proposed set of systems thinking skills to several of the more prominent systems thinking skill sets as a way to validate the coverage of the skills. The sets chosen are from the Waters Foundation (2014), Stave and Hopper (2007), Plate and Monroe (2014), and Meadows (2008). It should be noted that the Meadows Leverage Points are not intended to be systems thinking skills; they are ways to influence systemic outcomes (Meadows 2008). However, it is still important to ensure that they are covered by the proposed skill set. It is also important to note that the validation skills were mapped in the table using a “best-fit” strategy; they were placed in the most appropriate one or two (rather than the only one or two) relevant Arnold and Wade skills and/or domains.

Table 1: Systems Thinking Skill Mapping

#	Arnold & Wade Skill / Domain	Waters Foundation	Stave and Hopper	Plate and Monroe	Meadows
1	**Mindset**				Paradigms, Transcending Paradigms
1.1	Explore Multiple Perspectives	Changes Perspective			
1.2	Consider the Wholes and Parts	Big Picture		Understanding Systems at Different Scales	
1.3	Effectively Respond to Uncertainty and Ambiguity	Successive Approximation	Testing Policies		
1.4	Consider Issues Appropriately	Considers Issues Fully			
1.5	Use Mental Modeling and Abstraction	Assumptions, Mental Models	Using Conceptual Models		
2	**Content**				
2.1	Recognize Systems				
2.2	Maintain Boundaries				
2.3	Differentiate and Quantify Elements	Accumulations	Differentiating Types of Variables and Flows	Differentiating Types of Variables and Flows	Numbers, Buffers
3	**Structure**	System’s Structure, Leverage			Stock-and-Flow Structures, Rules, Paradigms, Transcending Paradigms
3.1	Identify Relationships	Connections	Recognizing Interconnections	Recognizing Interconnections	Information Flows, Goals
3.2	Characterize Relationships	Interdependencies	Recognizing Interconnections	Recognizing Interconnections	Information Flows, Goals
3.3	Identify Feedback Loops	Connections, Consequences, Time Delays	Identifying Feedback	Identifying Feedback	Delays, Balancing Feedback Loops, Reinforcing Feedback Loops
3.4	Characterize Feedback Loops	Interdependencies, Consequences, Time Delays	Identifying Feedback	Identifying Feedback	Delays, Balancing Feedback Loops, Reinforcing Feedback Loops
4	**Behavior**		Understanding Dynamic Behavior	Understanding Dynamic Behavior	Self-Organization
4.1	Describe Past System Behavior		Creating Simulation Models	Creating Simulation Models	
4.2	Predict Future System Behavior		Creating Simulation Models	Creating Simulation Models	

4.3	Respond to Changes over Time	Change Over Time			
4.4	Use Leverage Points to Produce Effects	Leverage		Incorporating Systems Thinking into Policies	Use of Leverage Points

The Waters Foundation systems thinking habits focus on the way a person thinks and acts when interacting with systems. This is exhibited in the way that the Waters skills fill out the Mindset domain. The Structure domain also maps well to the Waters skills. This shows that an understanding of the way systems are organized tends to influence the way a thinker acts when interacting with systems. Actions towards something are affected by perceptions about how that thing works.

Both the Stave and Hopper, and Plate and Monroe skill sets tend to map to the Structure and Behavior domains. This is reflective of their systems dynamics roots, and shows their emphasis on the *Using Insight* part of the Systems Thinking Spiral.

The Meadows leverage points, in general, tend to be ways of making systems produce desired outcomes (Meadows 2008). Therefore, the leverage points do not generally map to the Mindset skills, and only partly to the Content skills. Most of the leverage points are ways to change structure in order to influence system behavior. Intuitively, they are a good fit for the Structure domain.

Table 1 shows a common thread between all of the skill sets – a high concentration of skills around the Structure domain. Every skill set has at least one skill that maps to every Arnold and Wade Structure skill. As the original creator of the "systems thinking" term once said, "it's all about structure" (Richmond 1999).

Why a New Skill Set

Key questions drove the development of the set of systems thinking skills described in this paper:

- What core principles are universally similar between systems thinking skills described by different authors and experts?
- What are the different ways that these skills might work together as a system?
- How can the skills be described in a way that is measurable, accessible, and understandable?
- What are the interrelationships among these skills?
- Which of these skills are relevant under which contexts?
- How do these skills relate to the Arnold and Wade (2015) systems thinking definition?
- How can the many different facets of systems thinking be captured in a single skill set?

The proposed skill sets is an important step beyond the skill sets used for validation and others that have come before. The Arnold and Wade set is based upon a comprehensive definition of systems thinking published by Arnold and Wade (2015). It appears to be the first published definition that explicitly describes systems thinking as a system. Universally, the previous skill sets have been based upon definitions of systems thinking that have not done this. Ideally, the skills should derive from a systemic definition as they should be examined as a system to fully understand how they work.

Table 1 shows an interesting phenomenon: although the proposed skill set covers all skills in the comparative skill sets, the inverse is not true. Each of the skill sets that came before is in fact a sub-set of the Arnold and Wade skill set. Certain important skills, such as *Maintain Boundaries,* seem to be missing from the other sets. Also, some of the previous skill sets tend to emphasize the *Using Insight* part of the Systems Thinking Spiral (Stave and Hopper, Plate and Monroe, Sweeney and Sterman, Ossimitz) while others tend to emphasize the *Gaining Insight* part (Waters Foundation). This research seeks to assess both of those aspects of systems thinking, and thus requires a skill set that emphasizes both, along with their interactive and systemic natures.

The proposed skill set is organized in a way that can be assessed. Certain aspects of the previous skill sets are difficult to quantitatively assess. As one of several examples, assessing the skill of "Understanding Dynamic Behavior" as stated by Stave and Hopper (2007), seems difficult. How is that skill demonstrated? The Arnold and Wade skill set provides the skills *Describe Past Behavior* and *Describe Future Behavior*, which can be assessed by, simply, asking a thinker to do those things. Terminology such as "understanding" has been removed from the Arnold and Wade set and replaced with action verbs, as per current educational assessment guidelines.

The Arnold and Wade skill set is designed to be accessible outside the systems community. It organizes the skills into 4 simple and clear domains, then attempts to name and describe the skills in each domain using approachable terminology. Plate and Monroe took important steps towards clarification of their skills using accessible language (Plate and Monroe 2010), and the Waters Foundation describes their skills in an approachable way; however, many of the skill names and contents have remained esoteric. For example, the concepts of "Understanding Dynamic Behavior" or "Testing Policies" expressed in a number of previous systems thinking skill sets may not be intuitive to a mainstream educator lacking formal systems training. Yet, such educators are precisely the people that we need to pick up the systems thinking banner and carry it into mainstream school systems. Unfortunately, systems are complex and describing a systems thinking skill set verbally is not a simple ask. However, if the goal is to push systems thinking across community barriers to other fields, then approachable language is on the front lines

Conclusion

This paper has presented a complete set of systems thinking skills and maturity levels that can be applied widely to many different disciplines. These form a logical, sequential set of skills that can be used both in instruction and as a means of assessing one's system thinking capabilities. This set of skills were derived from a review of the literature, the application of systems thinking experience, and the application of systems thinking to itself.

Two facets of systems thinking, *Gaining Insight* and *Using Insight*, were described as a way to differentiate two types of systems thinking activity. Of the four skill domains in the proposed skill set, the Mindset skills tend to be used while gaining insight. The Content, Structure, and Behavior skills tend to be exercised while using insight. However, certainly, these boundaries are not meant to be confining. All skills may be used while both gaining and using insight while interacting with a system of interest.

The proposed skill descriptions will be the basis of future work in the development of simulations that will be used to automatically assess one's systems thinking skills and capabilities. It is likely that there will be a continued evolution of this skill set as these simulations are used to assess the systems thinking capabilities of novice and expert systems thinkers.

References

Arnold, R. D., & Wade, J. P. (2015). A Definition of Systems Thinking: A Systems Approach. *Procedia Computer Science*, *44*, 669–678. http://doi.org/10.1016/j.procs.2015.03.050

Boardman, J., Sauser, B., John, L., & Edson, R. (2009). The Conceptagon A Framework for Systems Thinking and Systems Practice. In *IEEE International Conference on Systems, Man, and Cybernetics* (pp. 3299–3304). San Antonio, TX.

Bonnema, G. M. (2012). Thinking Tracks for Integrated Systems Design. In *1st Joint International Symposium on System-Integrated Intelligence: New Challenges for Product and Production Engineering* (pp. 1–4). Hannover, Germany.

Burandt, S. (2011). Effects of an Educational Scenario Exercise on Participants' Competencies of Systemic Thinking. *Journal of Social Sciences*, *7*(1), 54–65.

Cuevas, N. M., Matveev, A. G., & Miller, K. O. (2010). Mapping General Education Outcomes in

the Major: Intentionality and Transparency. *Peer Review*, *12*(1).
Frank, M. (2012). Engineering Systems Thinking: Cognitive Competencies of Successful Systems Engineers. *Procedia Computer Science*, *8*, 273–278. http://doi.org/10.1016/j.procs.2012.01.057
Hatfield, G. (2011). Koffka, Köhler, and the "crisis" in psychology. *Studies in History and Philosophy of Biological and Biomedical Sciences*, *43*(2), 483–92. http://doi.org/10.1016/j.shpsc.2011.11.005
Hopper, M., & Stave, K. A. (2008). Assessing the Effectiveness of Systems Thinking Interventions in the Classroom. In *The 26th International Conference of the System Dynamics Society* (pp. 1–26). Athens, Greece.
International Council on Systems Engineering. (2014). A World in Motion: Systems Engineering Vision 2025. In *24th Annual INCOSE International Symposium*. Las Vegas: INCOSE.
Luong, J., & Arnold, R. D. (2016). Enhancing the Effects of Theatre of the Oppressed Techniques Using through Thinking: Reflections on an Applied Workshop. *Pedagogy and Theatre of the Oppressed Journal*, *1*(1).
Meadows, D. H. (2008). *Thinking in Systems: A Primer*. White River Junction, VT: Chelsea Green Publishing.
Ossimitz, G. (2000). Teaching System Dynamics and Systems Thinking in Austria and Germany. In *The 18th International Conference of the System Dynamics Society*. Bergen, Norway.
Ossimitz, G. (2002). Stock-Flow-Thinking and Reading stock-flow-related Graphs : An Empirical Investigation in Dynamic Thinking Abilities. *The 20th International Conference of The System Dynamics Society*, (May), 1–26. Retrieved from http://www.systemdynamics.org/conferences/2002/proceed/papers/Ossimit1.pdf
Plate, R. (2010). Assessing individuals' understanding of nonlinear causal structures in complex systems. *System Dynamics Review*, *26*(1), 19–33. http://doi.org/10.1002/sdr.432
Plate, R., & Monroe, M. (2014). A Structure for Assessing Systems Thinking. In *The 2014 Creative Learning Exchange*.
Richmond, B. (1991). Systems Thinking Four Key Questions. Lyme, NH.
Richmond, B. (1993). Systems thinking: Critical thinking skills for the 1990s and beyond. *System Dynamics Review*, *9*(2), 113–133. http://doi.org/10.1002/sdr.4260090203
Richmond, B. (1994). Systems Dynamics/Systems Thinking: Let's Just Get On With It. In *International Systems Dynamics Conference*. Sterling, Scotland.
Richmond, B. (2004). An Introduction to Systems Thinking: STELLA Software. In *An Introduction to Systems Thinking*. iseesystems, inc.
Senge, P. (1990). *The Fifth Discipline, the Art and Practice of the Learning Organization*. New York, NY: Doubleday/Currency.
Senge, P. M., Kleiner, A., Roberts, C., Ross, R. B., & Smith, B. J. (1994). *The Fifth Discipline Fieldbook: Strategies and Tools for Building a Learning Organization*. New York, NY: Doubleday/Currency.
Squires, A., Wade, J., Dominick, P., & Gelosh, D. (2011). Building a Competency Taxonomy to Guide Experience Acceleration of Lead Program Systems Engineers. In *9th Annual Conference on Systems Engineering Research (CSER)* (pp. 1–10). Redondo beach, CA.
Stave, K. A., & Hopper, M. (2007). What Constitutes Systems Thinking? A Proposed Taxonomy. In *25th International Conference of the System Dynamics Society*. Boston, MA.
Sterman, J. D. (2003). System Dynamics: Systems Thinking and Modeling for a Complex World. In *ESD International Symposium*.
Sweeney, L. B., & Sterman, J. D. (2000). Bathtub dynamics: initial results of a systems thinking inventory. *System Dynamics Review*, *16*(4), 249–286. http://doi.org/10.1002/sdr.198
Valerdi, R. (2012). Developing Systems Thinking Competencies through Facilitated Simulation Experiences. In *USC CSSE Annual Research Review*.
Vallero, D. A., & Letcher, T. M. (Trevor M. . (2013). *Unraveling environmental disasters*. Elsevier.
Wade, J., & Heydari, B. (2014). Complexity: Definition and Reduction Techniques Some Simple Thoughts on Complex Systems. *Proceedings of the Poster Workshop at the 2014 Complex*

Systems Design & Management International Conference, *1234*(18), 213–226.
Waters, J., & Waters, F. (2014). Waters Foundation Systems Thinking in Schools. Retrieved from http://watersfoundation.org/systems-thinking/overview
Zhang, P., Bodner, D. A., Turner, R. G., Arnold, R. D., & Wade, J. P. (2016). The Experience Accelerator: Tools for Development and Learning Assessment. In *2016 ASEE Annual Conference & Exposition*. New Orleans, LA: American Society for Engineering Education.

Biography

Mr. Ross David Arnold currently serves as senior research engineer for cooperative defense programs between the United States and Japan, where his work focuses on algorithm research, distributed systems, and emergent intelligence. He holds a BS in Computer Science from Rutgers University and an MS in Software Engineering from Stevens Institute of Technology. He is currently a PhD Candidate in Systems Engineering at Stevens, where his research focuses on systems thinking and related concepts.

Jon Wade is a Professor in the School of Systems and Enterprises at the Stevens Institute of Technology. He currently serves as the Director of the Systems and Software Engineering Division, as the Chief Technology Officer of the Systems Engineering Research Center (SERC) UARC and as the INCOSE Associate Director for Academic Research. Dr. Wade's research interests include complex systems, future directions in systems engineering research, and the use of technology in systems engineering and STEM education. Dr. Wade received his SB, SM, EE and PhD degrees in Electrical Engineering and Computer Science from the Massachusetts Institute of Technology.