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Javier Calvo-Amodio

The myriad of problems facing the world today are increasingly complex, dynamic, and transcend multiple domains necessitating the need for an equally complex and transdisciplinary approach to solve these problems. Systems thinking promises to provide the skills necessary for all citizens of the world, not just the experts, to handle these types of problems. The challenge is fostering the awareness and understanding of systems thinking necessary to cultivate a systems-literate society. Systems literacy is a promising and ongoing effort to establish a common systems language among all people, which requires establishing both the concepts and the path necessary to reach systems literacy. Systems thinking is founded on a set of four underlying concepts, or skills, that every systems thinker uses (distinctions, systems, relationships, and perspectives). The systems thinking learning path follows a process comprised of three levels – sensibility (awareness of systems), literacy (knowledge of systems), and capability (understanding of systems) – repeated across multiple phases. Recent educational curriculum has been developed to directly and indirectly teach these concepts to initial learners, or non-experts. However, no method to measure whether these initial learners are learning the underlying systems thinking concepts according to this learning process has been attempted. Hence, this research defines and measures the initial systems thinking learning process for non-experts. An experiment was conducted with 97 middle and high school students from the Science and Math Investigative Learning Experiences (SMILE) Program at Oregon State University to measure initial learning using the four systems thinking concepts across the three systems thinking learning levels. During the experiment, students were asked to complete a fish-tank system drawing while considering elements, interactions, and roles/purposes (Drawing A). Students were then taught about the systems thinking concepts and asked to complete a second fish-tank system drawing (Drawing B). Drawing A and B for each student were analyzed using a classification structure that classified each element, interaction, and role/purpose drawn according to the three systems thinking learning levels. Experimental results provide evidence to conclude that there is a statistically significant difference in the number of elements, interactions, roles/purposes, and the total of all three drawn by students from Drawing A to B. This indicates that teaching students to apply the systems thinking concepts as skills increases student learning of systems thinking. These exploratory results have the potential to support both future research efforts on systems thinking learning and educators who design systems thinking curriculum.

A Method for Measuring Systems Thinking Learning

by
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APPROVED:

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Head of the School of Mechanical, Industrial, and Manufacturing Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Seth Taylor, Author

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Chapter 1

1 Introduction

1.1 Background

Much of the foundation for scientific practice was established during the philosophical movement of logical positivism introduced by the Vienna Circle in the early 1900s (Suppe, 1977). Although this movement largely ceased by the 1970s, a way of thinking introduced by some Vienna Circle members called the reductionist approach is still common today as an approach to analyzing systems (Vienna Circle, 2016). The reductionist approach, or reductionism, breaks a system down into constituent parts and analyzes each part separately to gain an understanding of each part. From this understanding of each part, an understanding of the whole system is formed. Reductionism can be useful as a starting point in analysis; it is a way to simplify and begin to understand the parts of a system. However, when reductionism is relied upon to explain a system (a complex interrelated whole) in terms of its parts, a fallacy is committed (Sloane, 1945). Systems cannot be understood simply by gaining an understanding of the parts because a system is greater than the sum of its parts (Jackson, 2003). A system provides purpose for the parts and, more importantly, the interactions between the parts. Understanding these purposeful interactions yields an understanding of the whole system.

The alternative to a reductionist approach is a holistic approach. The holistic approach, or holism, seeks to understand the network of purposeful interactions between parts and how a system emerges as a result of the interactions (Jackson, 2003). In essence, the difference between reductionism and holism is a matter of perspective, or a difference in worldview, namely a reductionist perspective and a systemic perspective. A reductionist perspective adopts a reductionism worldview where parts explain systems, whereas a systemic perspective adopts a systemism worldview where everything is a system and systems explain parts (Bunge, 2000). If a worldview is simply a way of thinking, then systems thinking is a way of thinking about the world in terms of systems (Checkland, 1981).

Reductionism is limited to a mono-disciplinary approach for analyzing systems which often fails to provide the level of thinking necessary as complexity increases (Hofkirchner, 2016). Alternatively, systems thinking is able to provide multi-, inter-, and even trans-disciplinary approaches which can account for rising complexity. Complex problems, such as those that span multiple agencies and that constantly evolve, cannot be solved by breaking down and solving each part individually. Systems thinking promises to solve complex problems by establishing a common language for all people to collaborate and understand each other and the world as a whole. The systems thinking language provides a common perspective and can help align how people think real-world systems work with how systems actually work (Cabrera & Cabrera, 2015). Uniting the world using a common language is certainly a challenge, but like many challenges it begins with creating awareness.

Crowell (1992) and Tuddenham (2017) have advocated for the idea of systems literacy, which is an ongoing effort to foster awareness and understanding about systems among all people by establishing a common language. The systems literacy vision aligns with the ideas proposed by Ison and Shelley (2016) that systems thinking occurs across three levels: sensibility, literacy, and capability. Ison and Shelley (2016) posit that an investment in the fostering of systemic sensibility, or the awareness of systems, is a vital first step on the path to reach systems literacy and to affect the current trajectory of many complex problems facing the world today.

Although systems thinking lacks a unified definition, Cabrera (2006) is widely recognized for developing a robust definition of systems thinking by employing formal scientific methods. Cabrera, Colosi, and Lobdell (2008) propose that systems thinking is actually not a task to be performed, as it may seem, but rather the result of applying four simple rules to thinking. Cabrera (2006) first defined these four rules in the DSRP framework: 1) Distinction making (D), 2) Interrelating (R), 3) Organizing Systems (S), and 4) Perspective taking (P). These rules have been expressed in complex mathematical terms, but recent work by Cabrera and Cabrera (2015) has focused on making the four rules accessible and applicable for all audiences (p. 52):

- *Distinctions Rule (D):* Any idea or thing can be distinguished from the other ideas or things it is with;
- *Systems Rule (S):* Any idea or thing can be split into parts or lumped into a whole;
- *Relationship Rule (R):* Any idea or thing can relate to other things or ideas; and
- *Perspectives Rule (P):* Any thing or idea can be the point or the view of a perspective.

DSRP underlies all cognitive thought and is capable of empowering individuals to apply systems thinking to effect meaningful changes in the world. In the next section, an explanation for why systems thinking is not creating more systems thinkers is presented in order to establish the problem that this research addresses.

1.2 Problem Statement

The evolution from a reductionist perspective to a systems perspective is arguably one of the most crucial steps toward addressing the complex problems facing the world today and in the future. However, this evolution is not simple. The problem is rooted in complexity and the gap between reductionism and systemism in dealing with increasing degrees and kinds of complexity as conceptualized in Figure 1-1. Reductionism is the usual method of choice for analyzing systems and solving problems; it feels like a logical starting point to break a system or problem down into constituent parts to make it easier to understand. This method can become a fallacy, what Kahneman (2011, p. 158) calls “fail[ing] to apply a logical rule that is obviously relevant”, when it is relied upon to explain the whole system. Sloane (1945) calls reductionism a general fallacy rooted in social habit and tradition. The gap between reductionism and systemism might be explained by theory-induced blindness, or the widespread acceptance of a way of thinking that makes it difficult to notice any shortcomings (Kahneman, 2011, p. 277).

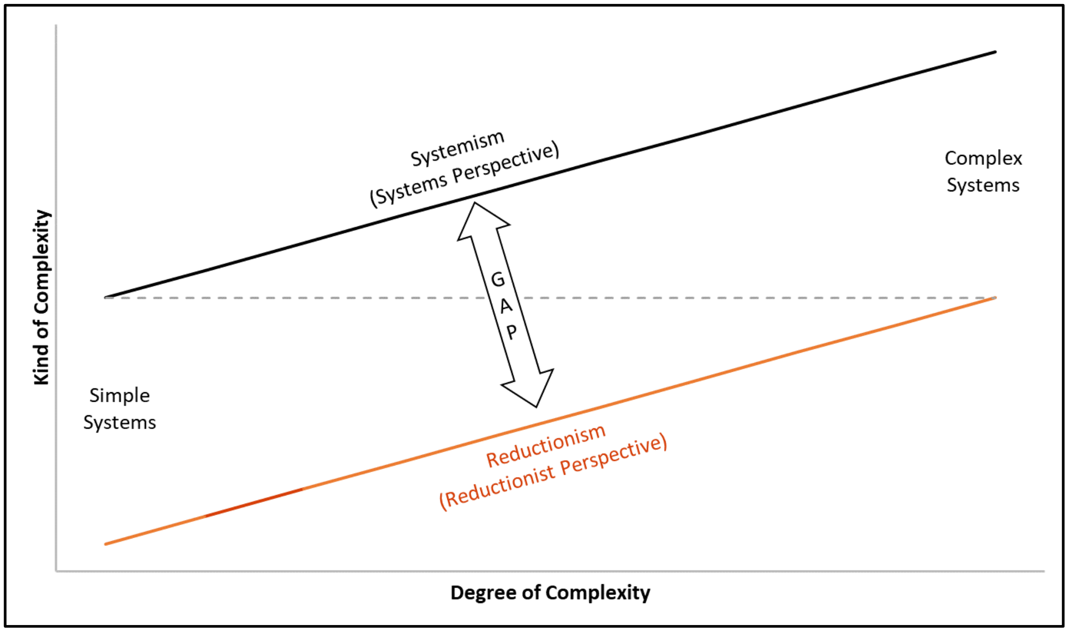

Figure 1-1: Gap between Reductionism and Systemism

Arguably, the most important and critical opportunity to overcome this gap is the education of the next generation of thinkers and problem-solvers in primary and secondary education (K-12). The growing need to integrate systems thinking into the curriculum has been recognized in K-12 education and has been addressed in recent educational standards such as the Next Generation Science Standards (NGSS Lead States, 2013). These standards are a positive step toward growing systems literacy; the standards have the ability to create the impetus for teachers and educators to implement systems thinking concepts into their curriculum. However, more systems thinking curriculum does not equate to more systems thinkers (Cabrera & Cabrera, 2015). Although increased curriculum equates to more awareness, it is still unclear whether this curriculum is creating more systems thinkers or whether this curriculum instills the underlying skills necessary to be a systems thinker.

In order to measure whether systems thinking curriculum equates to more systems thinkers, the fundamental concepts necessary to foster systems thinking learning must be identified and understood. However, before the concepts can be determined, the process by how a learner learns systems thinking, especially non-expert learners, must be understood. One way to understand this process is to measure it. Hmelo-Silver, Eberbach, and Jordan (2014) and Hmelo-Silver, Liu, Gray, and Jordan (2015) have measured K-12 student's understanding of complex systems according to a conceptual framework called the structure, behavior, function (SBF) framework. In studies with K-12 students, Hmelo-Silver et al. (2014) and Hmelo-Silver et al. (2015) found increased student understanding of aquarium systems using the SBF conceptual framework. This research provided greater understanding about how students learn systems thinking concepts, but this research did not directly measure the underlying skills to become a systems thinker or define the systems thinking learning process. Liu and Hmelo-Silver (2009) suggest that other conceptual frameworks, other than SBF, may exist to help students learn about systems. One such framework that exists is the DSRP framework developed by Cabrera (2006) which defines the underlying, or fundamental, systems thinking concepts. Since the systems thinking learning process is largely undefined for non-experts, there is an opportunity to define and measure this process according to those underlying skills necessary for a non-expert to become a systems thinker. Hence, the problem addressed in this thesis is the undefined and unmeasured initial systems thinking learning process for non-experts.

1.3 Research Questions

In order to address the research problem, the following four questions need to be answered.

1.3.1 First Question

Is there a statistically significant difference between the elements identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of distinctions?

1.3.2 Second Question

Is there a statistically significant difference between the interactions identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of relationships?

1.3.3 Third Question

Is there a statistically significant difference between the roles/purposes identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of perspectives?

1.3.4 Fourth Question

Is there a statistically significant difference between the totals of elements, interactions, and roles/purposes identified by non-experts in a fish-tank system drawing before and after learning about the three systems thinking concepts of distinctions, relationships, and perspectives?

1.4 General Hypotheses

In order to answer the four research questions, the following four hypotheses need to be addressed.

1.4.1 First Hypothesis

There is a statistically significant difference between the elements identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of distinctions.

1.4.2 Second Hypothesis

There is a statistically significant difference between the interactions identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of relationships.

1.4.3 Third Hypothesis

There is a statistically significant difference between the roles/purposes identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of perspectives.

1.4.4 Fourth Hypothesis

There is a statistically significant difference between the totals of elements, interactions, and roles/purposes identified by non-experts in a fish-tank system drawing before and after learning about the three systems thinking concepts of distinctions, relationships, and perspectives.

1.5 Research Purpose

The purpose of this research is to define and measure the initial systems thinking learning process for non-experts in the context of a fish-tank system to support future systems thinking curriculum development by and for non-experts.

1.6 Research Objectives

The objectives of this research were:

- To conceptualize the systems thinking curriculum development process by and for non-experts.
- To define the initial systems thinking learning process for non-experts.
- To design and conduct an experiment to measure the initial systems thinking learning process for non-experts.
- To contribute to the growth of systems literacy – which is the fostering of awareness and understanding of systems – in primary and secondary education (K-12).

1.7 Delimitations

In this section the limitations and assumptions for this research are presented.

1.7.1 Limitations

There were two limitations identified for this research. The first limitation was that the experiment conducted during this research was limited to middle and high school students participating in a pre-existing event hosted by the Science and Math Investigative Learning Experiences (SMILE) Program. Since only students from the SMILE Program were included in the experiment, the inferences drawn from the results of the experiment were limited to the SMILE student population and could not be generalized to all middle and high school students. The second limitation was that the experiment was conducted as part of a pre-existing event, where the SMILE Program expected that students were taught about systems thinking, so no control group could be included in the design of the experiment. The lack of a control group limited the separation of the results into expected student learning attributable to the repeated task of drawing a fish-tank system and systems thinking learning attributable to teaching students about the systems thinking concepts.

1.7.2 Assumptions

The assumptions made for this research were:

- Non-experts are individuals who have not received formal education on systems thinking and who lack an advanced level of awareness, understanding, and appreciation for systems. Non-experts have little to no systemic sensibility.
- Non-experts are capable of learning the systems thinking concepts of distinctions, systems, relationships, and perspectives.
- Drawing A and Drawing B of a fish-tank system used during the experiment were capable of measuring systems thinking learning.
- The systems thinking concept of systems (S) within the DSRP framework from Cabrera (2006) was measured for the initial learning phase of systems thinking as the total of the other three concepts of distinctions (D), relationships (R), and perspectives (P).
- Totals was equal to the sum of elements, interactions, and roles/purposes.

1.8 Relevance of this Study

In this section the needs for this research, from both a theoretical and practical perspective, and the benefits of this research are presented.

1.8.1 Need for this Research

There was a need to understand how to teach systems thinking to non-experts, what systems thinking concepts should be taught to non-experts, and how non-experts learn systems thinking in order to grow systems literacy in K-12 education. Therefore, a need existed for this research both theoretically and practically.

1.8.1.1 Theoretical Research Needs

The systems thinking learning process was largely undefined, especially the initial learning phase for non-experts with little to no systemic sensibility (or awareness of systems). Research that was able to define this process and measure the effect of teaching the underlying systems thinking concepts to non-experts would establish a theoretical starting point for teachers and educators to develop and adapt curriculum to teach systems thinking to non-experts.

1.8.1.2 Practical Research Needs

The real-world problems facing society today, like climate change and extreme poverty, are complex and dynamic. However, the real problem is how society thinks about these problems (Cabrera & Cabrera, 2015). Instead of people who overly rely on linear, static ways of thinking, the world needs more people who can think using a systems perspective and who can teach others how to think in this way. Research that focuses on fostering systemic sensibility as a way to grow toward a systems-literate society is paramount to alter the current trajectory of many problems facing society today (Ison & Shelley, 2016).

1.8.2 Benefits of this Research

This research had two benefits. First, this research benefitted the systems literacy movement by fostering greater systemic sensibility through increased awareness of the underlying systems thinking concepts and skills of every systems thinker. Second, since this research was exploratory, it benefitted future research endeavors focused on understanding how all people learn systems thinking and on improving how systems thinking is taught.

1.9 Research Outputs and Outcomes

The outputs and outcomes of this research were:

- A conceptual framework to help non-experts develop systems thinking curriculum for other non-experts.
- A conceptual model that defines the systems thinking learning process.
- Data and results from an experiment to measure initial systems thinking learning for non-experts in the context of a fish-tank system.
- One peer-reviewed conference paper that presents the conceptual framework for developing systems thinking curriculum by and for non-experts and the conceptual model for defining the systems thinking learning process.
    - Target Conference: *American Society for Engineering Management 2018 International Annual Conference*
    - See the full paper in Appendix A: ASEM Conference Paper
- One peer-reviewed journal article that presents the results from the experiment.
    - Target Journal: *Systems*

Chapter 2

2 Literature Review

2.1 Introduction

In this chapter the background knowledge for this research and for systems thinking education is presented, and the systems thinking curriculum development framework and systems thinking learning model are presented.

2.2 Background

In this section the three foundational concepts for this research are presented: systems, thinking, and systems thinking.

2.2.1 What is a System?

To understand the scope of the term “system”, one only needs to explore the sheer number of entries for the term in the *International Encyclopedia of Systems and Cybernetics* by Charles François (2004). The typical answer to the question of “what is a system?” has been to create a specialized definition to suit the needs of a given context. However, the proliferation of these specialized definitions has hindered the transferability of systems knowledge and language across disciplines and is one reason why systems concepts are not more widely adopted and consistently applied. In response to this problem, and in an effort to standardize the systems language, Rousseau, Billingham, and Calvo-Amodio (2018) provided an initial outline for an “Ontology of Systemology”. This ontology (which structures and organizes systems concepts and defines relationships between the concepts) establishes a general framework to answer this question.

There are two types of systems identified in the ontology, concrete systems and conceptual systems (Rousseau et al. 2018). Concrete systems are characterized by a persistent structure or persistent process and conceptual systems are characterized by persistent meaning. Both types of systems are composed of parts (also concrete or conceptual) which give rise to a specific system, or a whole, based on the structure and interrelationships of the parts

(Rousseau et al. 2018). Each system has a boundary which separates the parts and the system from the environment and the context in which the system lies. Additionally, each system can be viewed from a certain perspective which varies based on the viewer (Rousseau et al. 2018). Although the ontology continues past this point, the systems concepts provided here are the basic concepts necessary to recognize a system and are sufficient for this thesis.

2.2.2 What is Thinking?

The scope for the concept of thinking is as varied as the scope for the concept of a system. To limit the scope, only ways in which thinking was related to systems were considered. One way of thinking about systems, which was discussed in section 1.1, is reductionism. Reductionism is a simple and easy way of thinking about systems in order to reduce higher complexity to lower complexity (Hofkirchner, 2011). For example, thinking about a complex system, such as a living organism, easily elicits thinking in terms of the less complex parts that comprise the organism, such as organs or appendages. This simplification allows for identification of the complex system in terms of its parts, but this comes at the cost of diminishing complexity of the whole system. This is the main reason why a different approach other than reductionism is needed to think about and solve complex problems. The world and the problems facing it are increasing in complexity and therefore a way of thinking, like systems thinking, that is able to deal with this rising complexity is needed (Hofkirchner, 2017).

The gap between reductionist thinking and systems thinking might also be related to learning. Learning provides a way to challenge the traditional ways of thinking for without learning, new ways of thinking will be difficult to integrate across society. Deming (1994) eloquently expressed the relationship between thinking and learning as the theory of knowledge. Deming (1994) cautions that if the ways of thinking about the world, or theories, are not challenged then there is nothing to revise and therefore nothing to learn.

Ackoff (1999) has defined the content of learning by drawing distinctions between data, information, knowledge, understanding, and wisdom. Ackoff (1999) argues that these terms are not interchangeable and actually represent a distinct hierarchy with increasing value. Data is simply the basic form of learning, but data has no value until it is processed into the useful information. For example, think of data as a temperature, such as 90 degrees, and information as the temperature scale. Without the scale, a temperature is not useful because 90 degrees Fahrenheit is different than 90 degrees Celsius. Therefore, without information the right action to take based on data cannot be determined, such as how to dress for the weather. Therefore, data and information represent answers to questions of "what" (Ackoff, 1999). However, data and information cannot answer questions of "how" because this represents knowledge. Knowledge is obtained and revised based on experiences and theories, or ways of thinking. Therefore, knowledge represents how people think about the world and about systems (Ackoff, 1999). The acquisition of knowledge is facilitated by understanding. Understanding is able to answer questions of "why" (Ackoff, 1999). When current ways of thinking are not able to explain a problem, people seek to understand why in order to revise knowledge or the way of thinking about a problem. Data, information, knowledge, and understanding all contribute to wisdom which is an evaluated understanding of our way of thinking (Ackoff, 1999). Wisdom is knowing the best way to think about a problem and then being able to do the right things to address the problem. Wisdom can only be acquired as a result of challenging the current ways of learning and thinking, and systems thinking promises to provide an opportunity to challenge the reductionist ways of thinking.

2.2.3 What is Systems Thinking?

Similar to the concept of a "system", there are a significant number of specialized definitions for systems thinking. A general definition for systems thinking is that it is a systemic approach to studying all types of systems. The potential power of systems thinking rests on the transdisciplinary nature of systems thinking and how it can be used to draw from and apply ideas and concepts from all domains (Jackson, 2003). According to Checkland (1981), systems thinking is a particular way of, or a perspective for, thinking about the world; systems thinking uses the concept of a system to explain and understand complexity in the world. These answers to the question of “what is systems thinking?” offer an excellent starting point to understand systems thinking and how it relates the concept of systems with the concept of thinking. However, these definitions lack a way to apply systems thinking.

A robust definition of systems thinking is not complete without considering the underlying applications for this way of thinking. Rousseau et al. (2018) refer to Cabrera (2006) for developing the most robust definition of systems thinking. Cabrera (2006) first proposed four underlying rules for systems thinking called DSRP: 1) Distinction making (D), 2) Interrelating (I), 3) Organizing Systems (S), and 4) Perspective taking (P). Cabrera and Cabrera (2015) have refined the DSRP rules to make each one more accessible and applicable for everyone (p. 52):

- *Distinctions Rule (D):* Any idea or thing can be distinguished from the other ideas or things it is with;
- *Systems Rule (S):* Any idea or thing can be split into parts or lumped into a whole;
- *Relationship Rule (R):* Any idea or thing can relate to other things or ideas; and
- *Perspectives Rule (P):* Any thing or idea can be the point or the view of a perspective.

Systems thinking is actually not a task to be completed, but rather it is something achieved as a result of applying these four rules (Cabrera, Colosi, & Lobdell, 2008). Although all people implicitly use these four rules to guide thinking, a greater explicit understanding and use of these rules is a prudent challenge if the potential of systems thinking can help solve problems facing the world. Cabrera et al. (2008) posit that system thinking is easy to learn and practice, and, since it is applicable to any discipline or problem situation, it can even be algorithmically applied.

2.3 Systems Thinking Education

In this section the area of opportunity, or the gap, in systems thinking education for non-experts addressed by this research is presented.

2.3.1 Systems Thinking in Educational Standards

An effort to integrate systems thinking into the greater educational system is evident within recent educational standards such as the Next Generation Science Standards for primary and secondary education (K-12) (NGSS Lead States, 2013). The NGSS consist of three dimensions to learning: practices, core ideas, and crosscutting concepts. Systems and systems thinking concepts appear throughout the standards, but these concepts appear mostly in the dimension of crosscutting concepts. Learning that involves patterns, systems and system models, cause and effect, and structure and function are all systems concepts expressed in the NGSS (NGSS Lead States, 2013). The inclusion of systems and systems thinking concepts in these standards is a positive step toward fostering systemic sensibility. However, an explicit focus on the underlying systems thinking skills is not apparent in the standards and there is no mention of how to evaluate systems thinking learning.

2.3.2 Systems Thinking Education for Non-Experts

Although there is no evidence yet for widespread, established systems thinking courses in K-12, there are several localized examples of systems thinking in education. In this section three of those examples are presented to illustrate the area of opportunity in systems thinking education that this research addresses.

The first example of systems thinking education is the Creative Learning Exchange (CLE) which focuses on creating systems citizens by teaching K-12 students about systems thinking and systems dynamics concepts (CLE, 2019). The CLE was created in 1991 by Jay Forrester who is the founder of systems dynamics. The CLE offers an active, learner-based approach to teaching students by providing free access to curriculum that covers many systems and systems thinking topics. The CLE also connects its curriculum to established educational standards like the NGSS to complement what K-12 students learn in the classroom.

The second example of systems thinking education is the Open University (OU) in the United Kingdom. The OU specializes in distance (online) learning and offers several certificates and even advanced degrees for systems thinking practice, including an array of courses focused on the application of systems and systems thinking concepts (OU, 2019). Although this example is not targeted at K-12 audiences, as it is intended for college-level students, the curriculum from the OU demonstrates that systems thinking education spans all learning levels and is accessible to learners who have the drive and ability to pursue it.

The third example of systems thinking education is the work by Hmelo, Holton, and Kolodner (2000), Hmelo-Silver and Pfeffer (2004), Jordan, Hmelo-Silver, Liu, and Gray (2013), Hmelo-Silver, Eberbach, and Jordan (2014) and Hmelo-Silver, Liu, Gray, and Jordan (2015). Hmelo et al. (2000) designed methods of teaching to facilitate student learning about complex systems. This method centered around the framework of the SBF Theory, which stands for structures (S), behaviors (B), and functions (F). Structures were defined as the physical parts of a system, behaviors were defined as the purposes of the system or of the parts, and functions were defined as the mechanisms that allow structures to fulfill their functions (Hmelo et al., 2000). This theory demonstrated a promising conceptual framework to help students learn about complex systems. Hmelo-Silver and Pfeffer (2004) explored the differences between non-experts and experts in understanding complex systems such as an aquarium system. Hmelo-Silver and Pfeffer (2004) found that in drawings of an aquarium system, non-experts and experts differed the most in their understanding of system behaviors and functions and that non-experts struggled the most with understanding the invisible and dynamic processes associated with behaviors. Jordan et al. (2013) conducted a study with over one hundred middle school students to evaluate pre and post treatment understanding of an aquarium system using the SBF framework. Jordan et al. (2013) discovered that incorporating the SBF framework into instruction and explicitly targeting system relations significantly improved student understanding of all factors, especially for behaviors and functions. Hmelo-Silver et al. (2014) and Hmelo-Silver et al. (2015) developed and refined a scoring system to measure K-12 student's understanding about complex systems using the SBF framework. This scoring system distinguished between lower and higher levels based on the presence or lack of structures, behaviors, and functions in student descriptions of an aquarium system.

2.3.3 Systems Literacy

The idea of systems literacy was first introduced by Crowell (1992) as the capability for humans to understand and communicate about the world using systems. This paints systems literacy as a common language for all humans. Tuddenham (2017) defines systems literacy as an ongoing effort by all humans to foster awareness and understanding about systems. Although not explicitly called systems literacy, Cabrera and Cabrera (2015) recognize the promise that systems thinking has to establish a common language that facilitates shared understanding and collaboration. In essence, the goal of systems thinking education is to foster systems literacy. This opens the question of, how can systems literacy be achieved?

The roadmap for realizing systems literacy might be provided by Ison and Shelley (2016), who argue that systemic sensibility is available to all humans; humans understand, whether consciously or not, that all things are connected together. This idea of systemic sensibility is defined as our ability to see and be aware of systems in daily life. However, many people seem to lack the sensibility innately within us. Ison and Shelley (2016) note that the contexts, or educational outlets, that allow systemic sensibility to be fostered for all people is missing, and that society must make a shift in thinking from sensibility, to literacy, to capability as presented graphically in Figure 2-1. These three "levels" of systems thinking provide the foundation to define the systems thinking learning process.

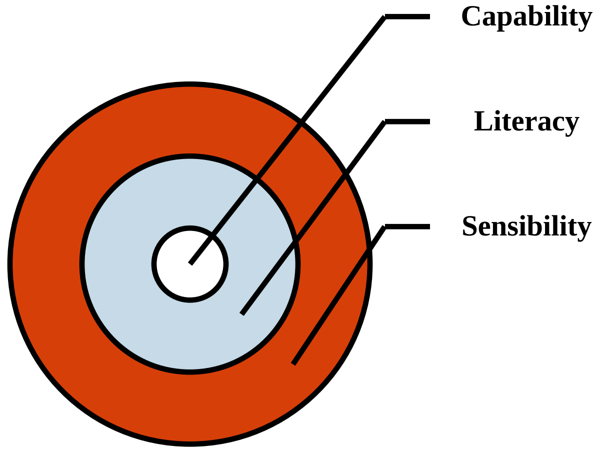

Figure 2-1: Systems Literacy Roadmap (adapted from Ison & Shelley, 2016).

To understand the three levels of sensibility, literacy, and capability each level can be defined in the context of thinking and learning about systems. According to Merriam Webster, one of the definitions for the word sensibility is “awareness of and responsiveness toward something” (Sensibility, n.d.). From this definition, and from the definition of sensibility related to systems provided by Ison and Shelley (2016), achieving sensibility about systems equates to achieving awareness about systems. The definition for literacy according to Merriam Webster is “the quality or state of being literate” (Literacy, n.d.), and one of the definitions for literate is “having knowledge or competence” (Literate, n.d.). Therefore, achieving literacy about systems equates to achieving knowledge about systems. The definition of capability according to Merriam Webster is, “the quality or state of being capable” (Capability, n.d.). The word capable has many meanings, one of which is “comprehensive” (Capable, n.d.). One of the definitions for the word comprehensive is “having or exhibiting wide mental grasp” (Comprehensive, n.d.). The word comprehensive is an adjective and the noun form of the word is comprehension, which means “the act or action of grasping with the intellect: understanding” (Comprehension, n.d.). Therefore, achieving capability about systems equates to achieving understanding about systems.

2.3.4 The Gap in Systems Thinking Education

In the previous sections the current work to integrate systems thinking into education and society was presented. Although the reference to systems and systems thinking concepts in educational standards is positive, systems thinking without systems thinkers will not create widespread change in how people see and solve problems in the world (Cabrera & Cabrera, 2015). The work by Hmelo et al. (2000), Hmelo-Silver and Pfeffer (2004), Jordan et al. (2013), Hmelo-Silver et al. (2014) and Hmelo-Silver et al. (2015) is also positive, but this work lacks both a connection to the systems thinking skills underlying all systems thinkers and a connection to a defined systems thinking learning process. Liu and Hmelo-Silver (2009) demonstrated that conceptual representations are a powerful way to affect student, or non-expert, learning about complex systems and suggest that other representations may exist with the same effect. The DSRP framework by Cabrera (2006) is another framework that can facilitate student learning about systems with a focus on those underlying skills. By connecting this framework to the systems literacy roadmap, the potential to bridge the gap between the systems thinking learning process and the underlying systems thinking skills is possible.

2.4 Systems Thinking Curriculum Development Framework for Non-Experts

In this section the systems thinking curriculum development framework for non-experts and the concepts that inform the framework are presented.

2.4.1 Framework Origins

The systems thinking curriculum development framework originated with the process design methodology created for a Capstone Senior Design course at Oregon State University. This 20-week course serves as a culminating project experience for senior undergraduate engineering students. The process design methodology for the course was created to address the unique needs of process-oriented projects assigned to industrial engineering students. For process-oriented projects, only a general idea of the problem is known at the onset of the project. This places a greater emphasis on student understanding of the current state of the problem and the processes and systems that the problem is embedded in before students can finalize a set of customer requirements. Due to the variety and level of complexity of projects, it became evident that incorporating systems thinking concepts into the design methodology could lead to increased student and project success. The traditional design process for Capstone projects follows the five-step problem-solving procedure of DMAIC (see section 2.4.3). Bolstering this structured process with a more systemic process like Soft Systems Methodology (Checkland, 1981) (see section 2.4.4) allowed students to better identify root causes of the problem during the initial stages of the project. Incorporating the System of Profound Knowledge (Deming, 1994) (see section 2.4.5) provided students with different perspectives to guide them through the current state analysis. These perspectives allowed students to more systemically analyze the current state and propose innovative project solutions. One of the projects involved with this course tasked students with creating systems thinking lessons, or curriculum, for non-experts which, after repeated success, has been developed into a framework composed of the systems thinking concepts briefly described here. In the following sections, each of the concepts that informed the framework are presented in greater detail.

2.4.2 Human-Activity Systems

The development of educational curriculum is an endeavor that interrelates both humans and human activities. As such, the development of curriculum entails designing a human-activity system. Checkland (1981) and Jackson (2003) both recognize human-activity systems as a key system type alongside natural, designed, and social systems. What makes a human activity system special is that it contains both people and activities and it intentionally pursues a purpose. Human activity systems emerge from a purpose, boundaries, relationships, and context (Calvo & Rousseau, 2019). Therefore, developing curriculum depends on designing a human-activity system.

2.4.3 DMAIC (Define, Measure, Analyze, Improve, Control)

The five-step, systematic problem-solving procedure known as DMAIC is commonly used by quality and process improvement practitioners. DMAIC is an acronym with each letter standing for one of the five steps: Define (D), Measure (M), Analyze (A), Improve (I), and

Control (C). Although this procedure is often associated with quality and process improvement activities (e.g. Six Sigma), it can be applied in any case where a general procedure is needed to manage and complete projects (Montgomery, 2013a). The goal of DMAIC is to identify problems (or opportunities), to determine root causes in order to correct processes or systems, and to develop and implement sustainable solutions. The main objectives for each step of the DMAIC procedure are detailed in Table 2-1.

Table 2-1: DMAIC Steps and Objectives (adapted from Montgomery, 2013a)

Step of DMAIC	Step Objectives
Define (D)	• Identify the problem or opportunity • Define customer requirements • Understand the relevant processes and systems
Measure (M)	• Evaluate the current state of the problem or opportunity • Collect data to measure current state performance
Analyze (A)	• Determine cause-and-effect relationships of the problem or opportunity based on data collected • Identify potential root causes
Improve (I)	• Create solution alternatives to address the problem or capitalize on the opportunity • Evaluate alternatives and select a final solution • Test and implement the final solution
Control (C)	• Monitor process and system performance after implementation • Ensure the implemented solution is sustained

Montgomery (2013a) and many practitioners tend to diagrammatically represent the DMAIC process in a linear, step-by-step fashion. However, the DMAIC process involves iteration and thus, can also be represented as a cycle (Sokovic, Pavletic, & Pipan, 2010). According to Montgomery and Woodall (2008), DMAIC is a generalization of the Plan-Do-Check-Act (PDCA) cycle that originated from the Shewart cycle which is “a dynamic scientific process of acquiring knowledge” (Shewart, 1939, p. 45). The DMAIC process is represented as a cycle in Figure 2-2. Representing the DMAIC process in this way established it as the backbone of the curriculum development framework and allowed it to be combined with more systemic, cyclical methodologies like Soft Systems Methodology.

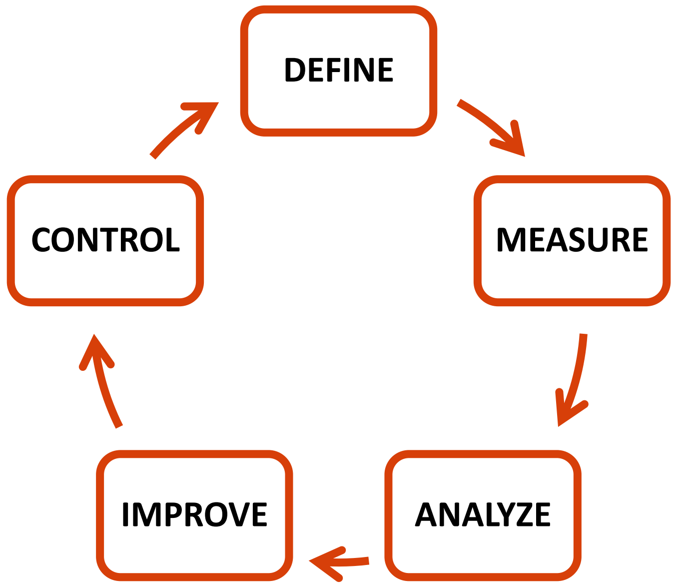

Figure 2-2: The DMAIC Process Represented as a Cycle

2.4.4 Soft Systems Methodology

Checkland (1981) developed Soft Systems Methodology (SSM) as a seven-stage cyclical learning system which is illustrated in Figure 2-3. The SSM system is an iterative process that allows a practitioner to learn about and understand a problem situation, or the domain in which the problem lies, as a system (Checkland, 1981). This process begins in the "real world" mode to identify key stakeholders and view the problem situation from different perspectives. The process then moves into the "systems thinking about the real world" mode to formulate root causes and create conceptual models of the system before returning to the "real world" mode to evaluate the models, define changes to be made, and take action. A popular method of SSM is known as CATWOE which aids in problem definition by identifying key stakeholders and considering multiple viewpoints. CATWOE, as described by Checkland (1981), is an acronym with each letter standing for a different perspective that should be considered:

- *(C) Customer* – A person who benefits or suffers from the system's activity.
- *(A) Actor* – A person who performs activities in the system.

- *(T) Transformation* – The conversion of inputs into outputs for a human activity system.
- *(W) Weltanschauung* – The world view that makes the human activity system meaningful to study.
- *(O) Owner* – A stakeholder who has the power to modify or destroy the system.
- *(E) Environmental* – The external constraints for a given system.

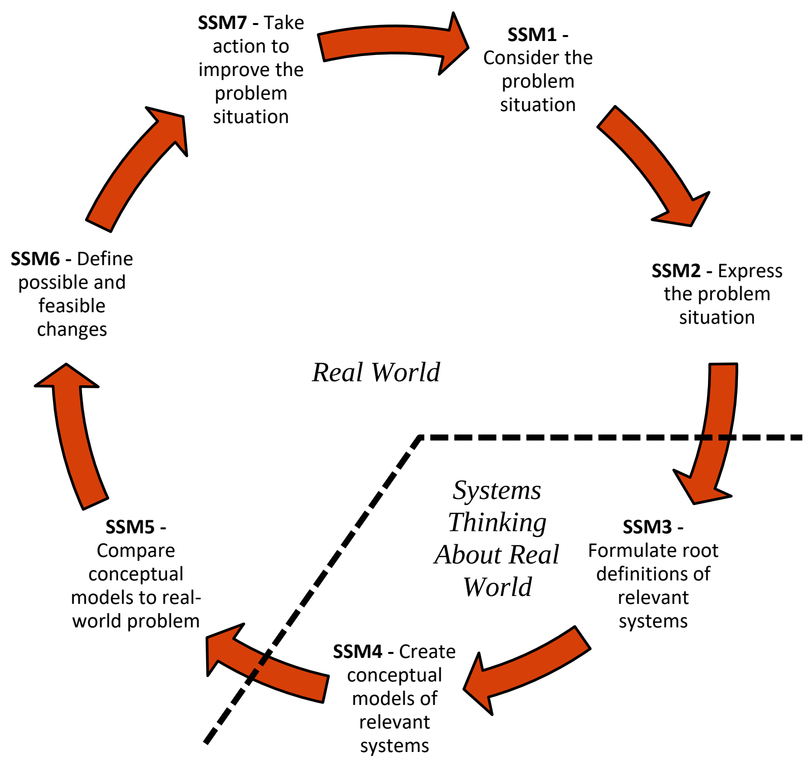

Figure 2-3: Soft Systems Methodology (adapted from Checkland, 1981, p. 163)

2.4.5 System of Profound Knowledge

Deming (1994) proposed the System of Profound Knowledge (SoPK) as a theory to help people understand the systems they are a part of. Deming (1994) argues that a system cannot understand itself and therefore requires an outside view, or perspective, which is provided by the SoPK. This theory of understanding systems is formed by four interrelated and inseparable parts, or perspectives, as depicted in Figure 2-4. Summarized, the four perspectives are:

(1) *Appreciation for a system* – "… a system is a network of interdependent components that work together to accomplish the aim of the system." (Deming, 1994, p. 95). The aim of a system is required otherwise no system can be defined. To fully appreciate a system, both the interdependence and the obligation of each component must be understood. The greater the interdependence in a system, the more important it will be for the system to communicate and coordinate. Individual components in a system must contribute their best to the system rather than seek to maximize their own self-interest.

(2) *Knowledge about variation* – "Life is variation." (Deming, 1994, p. 98). An analyst of a system must understand when system variation is from normal or non-normal (special) causes. If a system is stable, then its behavior can be predicted.

(3) *Theory of knowledge* – "The theory of knowledge helps us to understand that management in any form is prediction." Deming, 1994, p. 101). Knowledge is formed from theory. If a statement conveys some knowledge, can predict a future outcome while risking that the knowledge might be wrong, and past observations do not refute the statement, then that statement is a theory. Without theories, and revising those theories, no new knowledge can be generated and no learning can occur.

(4) *Psychology* – "Psychology helps us to understand people, interaction between people and circumstances…" (Deming, 1994, p. 107). The psychology perspective helps to understand the interactions between people and circumstances and between people and a system.

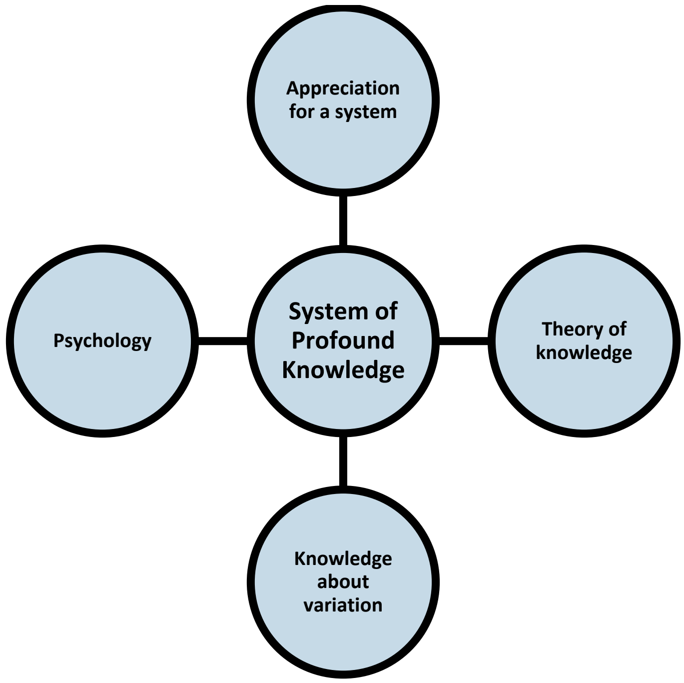

Figure 2-4: System of Profound Knowledge (adapted from Deming, 1994).

2.4.6 The Systems Thinking Curriculum Development Framework

The systems thinking curriculum development framework for non-experts was originally published as the "systems thinking lesson development model" by Taylor, Calvo-Amodio, and Well (2018) (see Appendix A: ASEM Conference Paper). The framework couples the systematic processes of DMAIC and SSM with the systemic approach of SoPK as shown in Figure 2-5. The combination of DMAIC and SSM forms a robust systems-based approach for a non-expert to develop curriculum. The SoPK provides the essential outside lens necessary for a non-expert to understand the human-activity system the curriculum is designed for. Notice that DMAIC is presented in the framework as DMAIIC. The first letter "I" stands for Innovate – to develop solution alternatives – and the second letter "I" stands for Implement – to select a solution alternative to implement. These two modifications were made to align stages 4, 5, 6 from SSM where conceptual models are created and compared to determine the best possible and feasible solution.

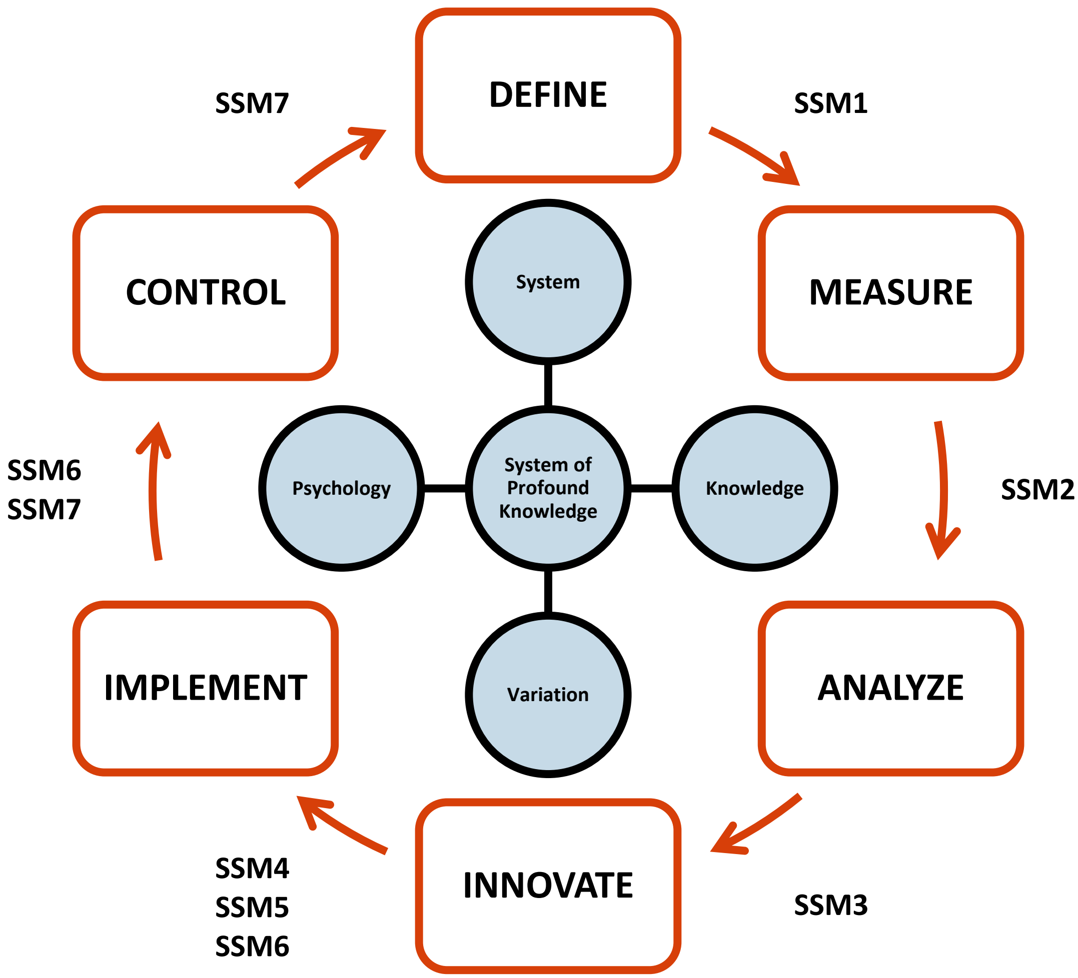

Figure 2-5: The Systems Thinking Curriculum Development Framework for Non-Experts (Taylor, Calvo-Amodio, & Well, 2018)

2.5 Systems Thinking Learning Model

In this section the learning curve which informed the shape of the systems thinking learning model is described before the complete model that defines the systems thinking learning process is presented.

2.5.1 S-Shaped Learning Curve

The design of the systems thinking learning model presented in this section is based upon an S-shaped learning curve. The mathematical basis for this type of curve is explained by the logistic equation introduced by Pierre-François Verhulst (Bacaër, 2011). This equation is a generalization of the equation for exponential growth, but with a limit on the maximum value to that growth. Although the logistic equation is used to model population growth, learners experience this same type of growth when learning a subject area. This growth is defined by a slow, then rapid increase represented by a positive curvature which appears convex in shape. At some point, this growth reaches an inflection point where growth continues to increase rapidly before levelling off at a maximum value to produce a negative curvature which appears concave in shape. Thus, this creates the distinctive S-shape curve (Bacaër, 2011). This curve represents the exponential growth associated with learning a subject and the “limit” to the knowledge one can acquire about a certain subject.

2.5.2 The Systems Thinking Learning Model

The systems thinking learning model was originally published by Taylor, Calvo-Amodio, and Well (2018) (see Appendix A: ASEM Conference Paper). The model illustrates the systems thinking learning process as shown in Figure 2-6. The model defines three distinct phases of learning along the S-shaped curve. The first learning phase is characterized by slow, initial learning and defined as Initial Learning (IL). The second learning phase is characterized by steep, exponential learning and defined as Rapid Learning (RL). The third learning phase is characterized by slowing, near-capacity learning and defined as Mastery Learning (ML).

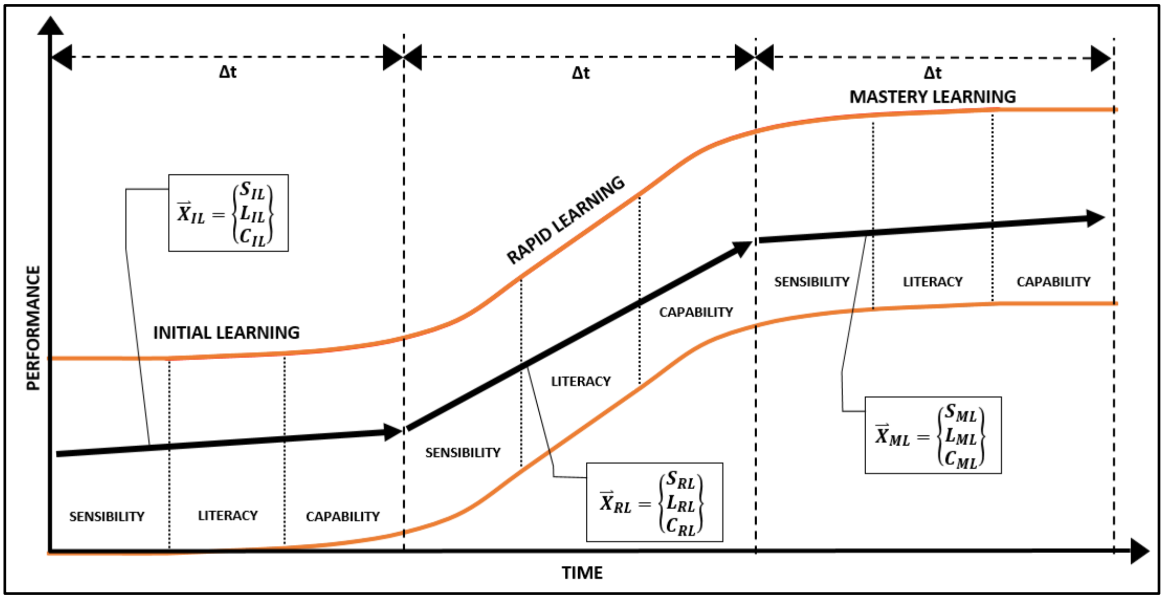

Figure 2-6: Systems Thinking Learning Model

Within each phase *i*, the systems thinking learning process goes through the three systems thinking learning levels of sensibility (S), literacy (L), and capability (C). All three levels are present concurrently during the systems thinking process. Therefore, a learner's path through each phase depends on a combination of all three levels. Performance (X) in each phase *i* can be measured according to Equation 2-1. A learner must demonstrate performance in all three levels to progress from one phase to the next. Of course, each learner is different so the time in each phase (Δt) can change. With this model, the systems thinking learning process has been defined and a general way of measuring that process has been proposed. In the following chapters, the methods used to define and measure the initial learning phase in the context of a fish-tank system are presented.

Equation 2-1: Measurement for each Systems Thinking Learning Phase

$$\vec{X}_i = \begin{Bmatrix} S_i \\ L_i \\ C_i \end{Bmatrix}$$

Chapter 3

3 Methodology

3.1 Introduction

In this chapter the research methodology is presented including, the research design, the testable research hypotheses, the collection and treatment of data, and the methodological issues and constraints.

3.2 Research Design

In this section the research design is presented including, the type of research, the research focus, the qualitative and quantitative methodologies, and the testable hypotheses.

3.2.1 Type of Research

The design of this research was a mix of both qualitative and quantitative methods. According to Leedy and Ormrod (2016), a mixed-methods research design can be employed for studies of human behavior where a combination of qualitative and quantitative methods will more completely answer a question than either approach could do individually. Since this research focused on student learning, it was well suited for a mixed-methods research design. The type of mixed-methods design used for this research was an exploratory design comprised of two phases, a qualitative phase first and quantitative phase second (Leedy & Ormrod, 2016).

During the qualitative phase of this research, data was collected during an experiment with middle and high school students to evaluate systems thinking learning (see section 3.3.1 for data collection details). The experiment consisted of asking students to draw two fish-tank systems while considering elements, interactions, and roles/purposes. Students were asked to complete the first fish-tank system drawing (Drawing A) at the beginning of the experiment. Then, students were asked to complete the second fish-tank system drawing (Drawing B) after students had been taught about the three systems thinking concepts of distinctions, relationships, and perspectives. According to Leedy and Ormrod (2016), this experimental design combines a one-group pretest-posttest design and a within-subjects design because of the order and timing of the drawings (A and B) and the treatment (i.e. teaching students about the systems thinking concepts). Utilizing this design allowed conclusions to be drawn about whether teaching the three systems thinking concepts helped students draw more elements, interactions, and roles/purposes for a fish-tank system because the treatment only affected the way students thought about fish-tank systems and did not affect their prior knowledge about fish tanks. After conducting the experiment, the collected drawings were analyzed using a content analysis. A content analysis was chosen because it allowed for a systematic examination of the contents of each drawing in order to code and record the frequency of elements, interactions, and roles/purposes drawn (Leedy & Ormrod, 2016). The content analysis methods are described in more detail in section 3.2.3. To improve the validity and reliability of the qualitative methods, an inter-coder agreement analysis was also conducted with two independent coders (see section 3.2.4 for details).

During the quantitative phase of this research, the frequency of elements, interactions, and roles/purposes recorded during the content analysis were analyzed using three inferential statistical tests (see section 3.2.5 for details). Analyzing the data using these tests allowed each of the testable hypotheses (presented in section 3.2.6) to be tested and allowed for conclusions to be drawn about whether there was a statistically significant difference between each drawing for each systems thinking concept. Additionally, the quantitative methods allowed inferences about systems thinking learning to be drawn with respect to the greater student population based on the groups of students in the experiment.

3.2.2 Research Focus

The focus of this research was to define and measure the initial systems thinking learning process for non-experts. This learning process was defined in section 2.5.2 as being comprised of three levels: 1) sensibility (awareness of systems), 2) literacy (knowledge of systems), and 3) capability (understanding of systems). An experiment was conducted to measure this process by asking students to draw a fish-tank system before (Drawing A) and after (Drawing B) learning to apply the systems thinking concepts of distinctions, relationships, perspectives, and systems (DSRP), proposed by Cabrera (2006), as skills. Students were taught the concept of distinctions as the skill of identifying elements in a system. Therefore, to measure student learning of distinctions the frequency of elements drawn was measured. Students were taught the concept of relationships as the skill of identifying interactions in a system. Therefore, to measure student learning of relationships the frequency of interactions drawn was measured. Students were taught the concept of perspectives as the skill of identifying roles/purposes in a system. Therefore, to measure student learning of perspectives the frequency of roles/purposes drawn was measured. Although students were not explicitly taught the concept of systems, student learning was measured by measuring the total frequency of elements, interactions, and roles/purposes. Measuring the systems thinking concepts in this way allowed for conclusions to be drawn about whether teaching students to apply these concepts as skills resulted in a statistically significant difference in systems thinking learning between Drawing A and Drawing B.

3.2.3 Qualitative Methods

The first step in a mixed-methods research design is a qualitative analysis to extract useful information from the collected data in preparation for a quantitative analysis (Leedy & Ormrod, 2016). For this research, a content analysis was used to identify patterns within the collected drawings in order to clearly define the different classifications of elements, interactions, and roles/purposes which could result from each pattern. This established a consistent and reliable classification structure, or methodology, which was used to classify each element (distinction), interaction (relationship), and role/purpose (perspective) that a student drew according to one of the three systems thinking learning levels (sensibility, literacy, or capability). Once each element, interaction, and role/purpose were classified, the frequency of each concept was recorded for each student in both Drawing A and Drawing B. In the following three sections, the methods for deriving the classification structure for each of the three systems thinking concepts are presented.

3.2.3.1 Classifying Distinctions (Elements)

The process of classifying distinctions meant classifying elements, which are the result of applying the systems thinking concept of distinctions. In the context of a fish-tank system, it was conceivable to define the elements that could be found inside the system boundary (i.e. within the fish tank) or that could interact with the system from outside the boundary. Therefore, the first step toward classifying elements was to define the elements for a fish-tank system. Table 8-1 in Appendix B: Element Classification Tables presents a list of forty-nine (49) elements that students could conceivably identify in a fish-tank system drawing based on an encyclopedia about marine aquariums by Mills (1987). Upon examining the list of elements, there are five distinguishable patterns:

(1) The first pattern is that some elements are visible while other elements are not visible (i.e. the element is invisible). For example, a plant is visibly identifiable in a fish-tank system whereas, bacteria are not visibly identifiable (i.e. cannot be seen with the naked eye).

(2) The second pattern is that some elements are inherently found inside of the fish tank (i.e. within the boundary of the fish tank) and some elements are inherently found outside of the fish tank. For example, elements like rocks and filters are found inside the system boundary while elements like a human and a thermostat are found outside the system boundary.

(3) The third pattern is that some elements are crucial in order to define a system as a fish-tank system. Without a fish, a tank, or water the system is unable to be defined as a fish-tank system whereas, the absence of a defined filter or a heater does not preclude defining a system with a fish, a tank, and water as a fish-tank system.

(4) The fourth pattern is the role that some elements have with the problem situation of the water in the fish tank turning green. In the context of this problem, some elements can be identified as underlying causes of that problem while many elements cannot be identified as underlying causes. The most likely underlying causes of green water in a fish-tank system include too much light or sunlight,

excess fish waste, decaying organisms, overfeeding resulting in uneaten food, and a broken or dirty (ineffective) filter or filtration system (Sharpe, 2019).

(5) The fifth pattern is that some elements are systems themselves, or at least can be defined or labeled as such. For example, the filter is actually just one element that belongs to the greater filtration system which can contain filter media, filter tubes, an impeller, and other elements.

The first pattern of visible or invisible was used to classify elements as either concrete elements (visible) or conceptual elements (invisible). Rousseau, Billingham, and Calvo-Amodio (2018) define concrete elements, or systems, as having a persistent structure and conceptual elements as having a persistent meaning. Rousseau et al. (2018) define conceptual elements as non-physical elements so it may seem that this classification logic is not appropriate. However, elements like bacteria or electricity, although each has a physical structure at some level, cannot be seen with the naked human eye. Additional reasoning for this classification logic was drawn from a study about student learning of complex systems by Hmelo-Silver and Pfeffer (2004) who determined that students tend to recall "perceptually salient" structures, or elements, more readily than less salient structures or elements. Therefore, classifications to distinguish visible, more salient elements from invisible, less salient elements were needed to fully classify elements in a fish-tank system.

The second pattern of inside or outside the system boundary (i.e. the fish tank) was used to classify elements that are either internal or external. Similar to elements that are visible, elements that are inside the fish-tank system are more salient than elements that are outside the fish-tank system. When considering a fish-tank system, thinking about internal elements is more likely to occur first than thinking about elements in the external environment around the fish tank. Therefore, classifications to distinguish internal elements from external elements were needed to fully classify elements in a fish-tank system.

The remaining patterns of 3) elements being critical to the system definition, 4) elements being underlying causes of the problem situation, and 5) elements being sub-systems within the greater fish-tank system were used to create three more element classifications. Examining these three patterns revealed a connection to three of the ideas from the content of learning by Ackoff (1999): data and information, knowledge, and understanding. Elements that are critical to define a fish-tank system represent the essential data or information used to define what type of system is being observing (Ackoff, 1999). Defining essential elements demonstrates an awareness of what elements are necessary to define a system as a fish-tank system. Therefore, a classification to distinguish essential elements from other elements was needed to fully classify elements in a fish-tank system. Elements that are underlying causes of the problem situation or elements that are sub-systems represent an advanced understanding of why a system behaves a certain way (Ackoff, 1999). Defining advanced elements demonstrates an understanding of why elements might be causing the green water problem situation in a fish-tank system. Therefore, a classification to distinguish advanced elements from other elements was needed to fully classify elements in a fish-tank system. Elements that do not meet the essential or advanced classification definitions still contribute knowledge about how a system works (Ackoff, 1999). Defining these secondary elements demonstrates knowledge about the elements needed to explain how the system is working. Therefore, a classification to distinguish secondary elements from other elements was needed to fully classify elements in a fish-tank system. The connections between the five patterns and the seven element classifications are summarized in Table 3-1.

Table 3-1: Element Patterns and Element Classifications

Pattern	Classification	Definition
(1) Visible or invisible elements	Concrete Elements	A concrete element is visible (i.e. it can be seen with the naked human eye). Examples: fish, plants, filter.
	Conceptual Elements	A conceptual element is invisible (i.e. it cannot be seen with the naked human eye). Examples: bacteria, Oxygen, Nitrogen.

Pattern	Classification	Definition
(2) Elements inside or outside the system boundary	Internal Elements	An internal element is located primarily inside of the system boundary (i.e. the fish tank). Examples: rocks, fish food, air/water pump.
	External Elements	An external element is located primarily outside of the system boundary (i.e. the fish tank) in the environment. Examples: fish net, sunlight, tank stand.
(3) Elements that are critical to the system's definition; (4) Elements that are underlying causes of the problem; (5) Elements that are labeled as systems	Essential Elements	An essential element is crucial data or information used to define what a fish-tank system is. Without an essential element, the system cannot be defined as a fish-tank system. For a fish-tank system, the essential elements are fish, tank, and water.
	Secondary Elements	A secondary element enhances knowledge about how a fish-tank system works. The addition or removal of a secondary element does not affect the definition of a fish-tank system. Examples: filter, algae, human.
	Advanced Elements	An advanced element enhances understanding about why the fish-tank system is behaving the way it is. Advanced elements include all conceptual elements, elements that are underlying causes of the problem situation, and elements that are labeled as sub-systems within the greater fish-tank system. Examples: ammonia, bacteria, filtration system, dead organisms.

In order to classify each element according to one of the three systems thinking learning levels, the combinations of classifications that belonged at each level needed to be defined. In section 2.3.3 the three levels were defined as: 1) sensibility – awareness of systems, 2) literacy – knowledge of systems, and 3) capability – understanding of systems. These definitions were congruent with the three element classifications of essential, secondary, and advanced respectively. Therefore, essential elements were classified at the sensibility level, secondary elements were classified at the literacy level, and advanced elements were classified at the capability level. Since essential elements were constrained to fish, tank, and water, which are all concrete and internal elements, this resulted in only one combination of classifications for elements at the sensibility level. Secondary elements cannot be classified as conceptual, but these elements can be classified as internal or external. This resulted in two combinations of classifications for elements at the literacy level. Advanced elements can be classified as conceptual and also as concrete, and, just like secondary elements, advanced elements can be classified as internal or external elements. This resulted in four combinations of classifications for elements at the capability level. The element classification combinations for each systems thinking learning level are summarized in Table 3-2.

Table 3-2: Element Classifications and Systems Thinking Learning Levels

Learning Level	**Classification**	**Description**
Sensibility	1. Concrete, Internal, Essential Elements	All elements at the sensibility level are essential, meaning these elements are necessary in order to define a system as a fish-tank system. Additionally, all elements at this level are visible and are found inside the fish-tank system boundary.
Literacy	1. Concrete, Internal, Secondary Elements	All elements at the literacy level are secondary, meaning these elements enhance knowledge about how the fish-tank system works. Additionally, all elements at this level are visible and can be found both inside and outside the fish-tank system boundary.
	2. Concrete, External, Secondary Elements	
Capability	1. Concrete, Internal, Advanced Elements	All elements at the capability level are advanced, meaning these elements enhance understanding about why the fish-tank system is behaving the way it is. Additionally, elements at this level can be either visible or invisible and can be found both inside and outside the fish-tank system boundary.
	2. Concrete, External, Advanced Elements	
	3. Conceptual, Internal, Advanced Elements	
	4. Conceptual, External, Advanced Elements	

The classification structure was now used to classify each of the elements defined for a fish-tank system according to the systems thinking learning levels. The element classification flowchart used during the classification process is presented in Figure 3-1.

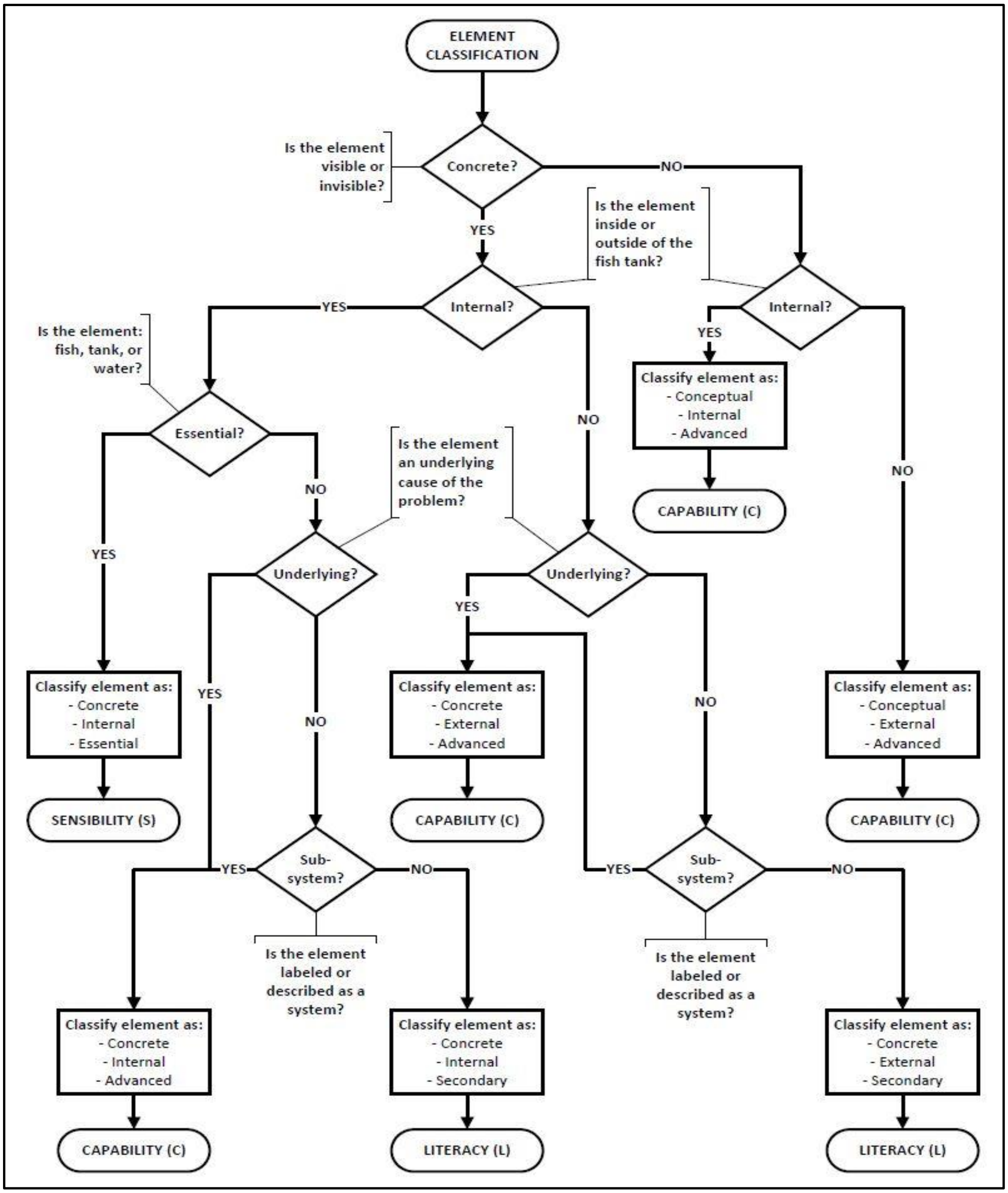

Figure 3-1: Element Classification Flowchart

The list below provides three (3) examples of how the element classification process works using the flowchart. The classifications for all forty-nine (49) elements defined prior to the data analysis are presented in Table 8-2 in Appendix B: Element Classification Tables.

(1) Fish

- *Concrete?* Yes, a fish is concrete, or visible with the naked human eye.
- *Internal?* Yes, a fish is located primarily inside the fish-tank system boundary.
- *Essential?* Yes, a fish is a necessary element to define a fish-tank system.
- Therefore, a fish is classified as a *concrete, internal, essential element* which is classified at the *sensibility* level.

(2) Human

- *Concrete?* Yes, humans are concrete, or visible with the naked human eye.
- *Internal?* No, humans are located primarily outside the fish-tank system boundary which makes a human an external element.
- *Underlying?* No, humans may play a role in causing the green water problem, but humans are not an underlying cause.
- *Sub-system?* No, however, technically humans are a system. If a student used the label of "human system" a human would be considered a system, but if labeled as just "human" this was not considered a sub-system.
- Therefore, a human is classified as a *concrete, external, secondary element* which is classified at the *literacy* level.

(3) Electricity

- *Concrete?* No, electricity, or the flow of electrons, is not visible with the naked human eye.
- *Internal?* No, electricity is located primarily outside the fish-tank system boundary.
- Therefore, electricity is classified as a *conceptual, external, advanced element* which is classified at the *capability* level.

The element classifications were now used to analyze each drawing and record the frequency of elements drawn according to specific rules in preparation for the quantitative analysis. The rules used to classify and record elements are described in Table 3-3.

Table 3-3: Rules for Classifying and Recording Elements

Rule #	**Rule Description**	**Example (if necessary)**
1	An element must be drawn or described using words to be recorded.	
2	An element does not need to be labeled using words to be recorded.	
3	An element must be drawn, labeled, and/or described in a "distinguishable" manner to be recorded. A "distinguishable" element is recognizable or identifiable at first glance without extra effort.	
4	An element that is drawn and labeled using words shall be recorded exactly as the label is written.	Suppose the element "air/bubbles" are drawn and labeled as "oxygen". Therefore, the element "oxygen" is recorded and not the element "bubbles".
5	Elements must be classified independently for each drawing (i.e. elements classified in Drawing A cannot influence the elements classified in Drawing B, and vice versa, for the same student or between students).	Suppose student *j* draws an undistinguishable "blob" in Drawing A with no label. In Drawing B, the student draws the same "blob" with the label of "food". The "blob" in Drawing A should not be recorded as the element "food" since it is an undistinguishable element when evaluated independently
6	If an element is not drawn, labeled and/or described in a distinguishable manner, or if the element is not relevant for a fish-tank system, the element shall not be recorded.	The element "cat" is not considered relevant to a fish-tank system unless it is explicitly connected to other elements or the system. For example, if a student describes how a "cat" tries to get the fish this means the cat is relevant to the system and can be classified (if necessary) and recorded.
7	If two (2) or more instances of the same element are drawn, labeled, and/or described, only one (1) instance of that element shall be recorded per drawing.	If a student draws multiple elements that look like "plants" only one (1) instance of the element "plants" is recorded.

Rule #	Rule Description	Example (if necessary)
8	If an element that is not included in the defined list of elements (see Table 8-1 and Table 8-2 in Appendix B: Element Classification Tables) prior to analysis is drawn, labeled, and/or described, and the element is relevant to a fish-tank system, the element shall be classified using the flowchart (Figure 3-1) and recorded.	The element "cat" as described in rule #5.
9	An element classified at the sensibility level is assigned a score of one (1). An element classified at the literacy level is assigned a score of two (2). An element classified at the capability level is assigned a score of three (3).	*For sensibility:* fish, tank, water *For literacy:* filter, human, fish food, plants, etc. *For capability:* electricity, bacteria, broken filter, filtration system, etc.
10	The "tank" element shall always recorded for Drawing B because it is pre-drawn on the worksheet, even if the "tank" is not labeled and/or described.	
11	The "tank cover (lid)" element shall only be recorded if it is described or labeled in words as "tank cover" or "tank lid". A "tank cover (lid)" element that is drawn shall not be recorded.	
12	The "filtration system" element shall only be recorded if it is described or labeled in words as "filter system" or "filtration system".	
13	The "impeller" element shall only be recorded if it is drawn, labeled, or described separately from a "filter" or "filtration system" element.	Suppose an impeller is drawn inside a filter, therefore the "impeller" element shall not be recorded as a separate element.

3.2.3.2 Classifying Relationships (Interactions)

The process of classifying relationships meant classifying interactions, which are the result of applying the systems thinking concept of relationships. In the context of a fish-tank system, it would be conceivable to define all the possible interactions that could take place between elements. However, defining all of these interactions was not realistic. Suppose that each of the forty-nine (49) elements defined in Table 8-1 in Appendix B: Element Classification Tables had at least one interaction with every other element. This would result in forty-eight (48) interactions per element meaning, at a minimum, $48^2 = 2{,}304$ interactions would need to be defined. Instead of defining an exhaustive list of all possible interactions, the classification structure developed for interactions was based upon the simple patterns necessary to classify all potential interactions that students could conceivably identify for a fish-tank system.

The simple patterns of interactions were determined from the systems thinking concept of relationships (R) within the DSRP framework from Cabrera (2006). Cabrera and Cabrera (2015) define relationships as the interplay between action and reaction, which are the two underlying concepts required for all relationships. The expression of a relationship at the simplest level means using a line to connect two elements together. However, this connection lacks any knowledge or understanding about the action and the reaction that is occurring between the two elements. Using a line to connect two elements only demonstrates awareness that a relationship exists, which aligns with the sensibility level of systems thinking learning. To reach the upper two levels of systems thinking learning, one must demonstrate knowledge (literacy) about how the elements are interacting or about how a relationship between elements causes an effect and understanding (capability) about why certain actions cause certain effects (i.e. a cause-and-effect relationship). Therefore, the patterns identified for interactions focused on the presence of or the lack of actions and reactions, and the combination of those two concepts for each interaction, which resulted in four patterns: 1) non-action, non-reaction interactions; 2) action, non-reaction interactions; 3) non-action, reaction interactions; and 4) action, reaction interactions.

The first pattern of non-action, non-reaction interactions immediately established two classifications to distinguish interactions. The first classification was for non-action interactions, or an interaction that lacks a clearly defined action, and the second was for non-reaction interactions, or an interaction that lacks a clearly defined reaction. The combination of these two classifications is synonymous to drawing a line between two elements to demonstrate awareness of a relationship, which does not define a clear action or reaction. As explained previously, an interaction that only demonstrates awareness resides at the sensibility level of systems thinking learning. Cabrera and Cabrera (2015) describe a line connecting two elements as a *simple* way to visualize relationships. Therefore, a classification to distinguish simple interactions from other interactions was needed to fully classify interactions for a fish-tank system.

The second pattern of action, non-reaction interactions and the third pattern of non-action, reaction interactions immediately established two additional classifications to distinguish interactions. The first classification was for action interactions, or an interaction that includes a clearly defined action, and the second was for reaction interactions, or an interaction that includes a clearly defined reaction. Both of these patterns tell only half the story for an interaction, either an action without a reaction or a reaction without an action. As explained previously, these types of interactions reside at the literacy level of systems thinking learning because these interactions express knowledge about how elements are interacting or about how a relationship causes a reaction. Therefore, a classification to distinguish half-developed, or intermediate, interactions from other interactions was needed to fully classify interactions for a fish-tank system.

The fourth pattern of action, reaction interactions tells the full story for an interaction. As explained previously, interactions with both a clearly defined action and reaction reside at the capability level because these interactions express understanding of why a specific action between elements causes a specific reaction. Similar to the classification for advanced elements, this level of thinking about interactions is also advanced. Therefore, a classification to distinguish advanced interactions from other interactions was needed to fully classify interactions for a fish-tank system. The connection between the four patterns and the seven interaction classifications are summarized in Table 3-4.

Table 3-4: Interaction Patterns and Interaction Classifications

<table>
<tr><th>Pattern</th><th>Classification</th><th>Definition</th></tr>
<tr><td rowspan="3">(1) Non-action and non-reaction interactions</td><td>Non-action Interactions</td><td>A non-action interaction does not explain how or why two or more elements are interacting. No clear action is defined.</td></tr>
<tr><td>Non-reaction Interactions</td><td>A non-reaction interaction does not explain the effect(s) of an interaction between two or more elements. No clear reaction is defined.</td></tr>
<tr><td>Simple Interactions</td><td>A simple interaction demonstrates awareness that two or more elements relate, or that the elements are interacting in some way, but no clear action and no clear reaction is defined.</td></tr>
<tr><td rowspan="2">(2) Action and non-reaction interactions</td><td>Action Interactions</td><td>An action interaction does explain how two or more elements are interacting. A clear action is defined.</td></tr>
<tr><td rowspan="2">Intermediate Interactions</td><td rowspan="2">An intermediate interaction demonstrates awareness that two or more elements relate, or that the elements are interacting in some way, and also demonstrates knowledge about either the action (how two or more elements are interacting) or the reaction (the effect(s) of an interaction between two or more elements).</td></tr>
<tr><td rowspan="2">(3) Non-action and reaction interactions</td></tr>
<tr><td>Reaction Interactions</td><td>A reaction interaction does explain the effect(s) of an interaction between two or more elements. A clear reaction is defined.</td></tr>
<tr><td>(4) Action and reaction interactions</td><td>Advanced Interactions</td><td>An advanced interaction demonstrates both the awareness that two or more elements relate and the knowledge of actions and reactions, and also demonstrates the understanding of the interplay between the action and reaction (i.e. the cause-and-effect relationship).</td></tr>
</table>

Additional evidence for why simple, intermediate, and advanced interactions should reside at the systems thinking learning levels of sensibility, literacy, and capability respectively was drawn from a similar study by Hmelo-Silver, Eberbach, and Jordan (2014) who distinguished different structures, behaviors, and functions (SBF) across multiple levels of thinking while classifying aquarium system drawings (see section 2.3.2 for background details on SBF). The lower level of thinking was classified as only the identification of some relationship between structures, but the lack of any elaboration (Hmelo-Silver et al., 2014). The middle level of thinking was classified as the identification of a structure in relation to either a behavior or a function (Hmelo-Silver et al., 2014). For example, a connection between a behavior and a structure described how a structure performed its function, such as “fish swim in water”, while a connection between a structure and a function described the effect of a structure’s behavior, such as “fish move around the tank”. The upper end of thinking was classified as the identification of a structure in relation to both a behavior and a function (Hmelo-Silver et al., 2014). This level of thinking demonstrated both how a structure performed its function and the effect of that behavior, such as “fish swim in water to move around the tank”. From each of these levels of thinking by Hmelo-Silver et al. (2014), comparisons could be drawn to each of the systems thinking learning levels defined in this research. From the lower level, comparisons could be drawn to awareness of simple relationships and the classification of sensibility. From the middle level, comparisons could be drawn to knowledge of separate action and reaction relationships and the classification of literacy. From the upper level, comparisons could be drawn to understanding of the cause-and-effect relationships and the classification of capability. The interaction classification combinations for each systems thinking learning level are summarized in Table 3-5.

Table 3-5: Interaction Classifications and Systems Thinking Learning Levels

Learning Level	**Classification**	**Description**
Sensibility	1. Non-action, Non-reaction, Simple Interactions	All interactions at the sensibility level are simple, meaning interactions only demonstrate an awareness that two or more elements relate. Interactions at this level do not explain how two or more elements are interacting or the effect(s) of the interaction between two or more elements. No clear action or reaction is defined.
Literacy	1. Action, Non-reaction, Intermediate Interactions	All interactions at the literacy level are intermediate, meaning interactions demonstrate awareness that two or more elements relate and knowledge about either how two or more elements are interacting or the effect(s) of the interaction between two or more elements. In case (1) where a clear action is defined, no clear reaction is defined. Alternatively, in case (2) where a clear reaction is defined, no clear action is defined.
	2. Non-action, Reaction, Intermediate Interactions	

Learning Level	Classification	Description
Capability	1. Action, Reaction, Advanced Interactions	All interactions at the capability level are advanced, meaning interactions demonstrate both awareness that two or more elements relate and knowledge about the actions and reactions between two or more elements, and also an understanding of why the action causes the reaction. A clear cause-and-effect relationship is defined.

The classification structure could now be used to classify potential interactions identified by students for a fish-tank system. The interaction classification flowchart used during the interaction classification process is presented in Figure 3-2. While analyzing each drawing, interactions were classified and recorded according to specific rules in preparation for the quantitative analysis. The rules used to classify and record interactions are described in Table 3-6.

Table 3-6: Rules for Classifying and Recording Interactions

Rule #	Rule Description	Example (if necessary)
1	An interaction must involve two (2) or more distinguishable elements to be recorded.	"The fish swims" is not an interaction because only one element ("fish") is involved. This statement would not be recorded as an interaction.
2	An interaction must be denoted (drawn) either with arrows/lines or described using words to be recorded (an interaction might be denoted using both arrows/lines and written descriptions).	A line drawn between the elements of "fish" and "food" denotes an interaction between these two elements (at the sensibility level). The description "the fish eats the food" also denotes an interaction between the elements of "fish" and "food" (at the literacy level).
3	An interaction must be drawn and/or described in a "distinguishable" manner to be recorded. A "distinguishable" interaction is recognizable or identifiable at first glance without extra effort.	

Rule #	Rule Description	Example (if necessary)
4	Only one (1) interaction shall be assigned between two elements. If multiple interactions are assigned between two elements, then only the interaction classified at the higher systems thinking learning level shall be recorded.	Suppose two interactions, "fish eat food to gain energy" and "fish play with food", have been assigned between the two elements of "fish" and "food". Since the interaction of "fish eat food to gain energy" is classified at a capability level (both an action and a reaction are defined), only this interaction shall be recorded between the two elements "fish" and "food".
5	Interaction descriptions must be phrased using verbs, with the exception of the verbs: *add, make, give, gave, get, got, keep, help, is, are, allow, or provide*. Descriptions using these verbs shall be recorded as a role/purpose and not an interaction.	The description "the fish swims in the water" is recorded as an interaction. However, the description "the fish is swimming in the water" is recorded as a role/purpose because the linking verb "is" is used in the description.
6	A part of a drawing or a description that is recorded as an interaction cannot also be recorded as a role/purpose unless both an interaction and a role/purpose are distinguishable.	Suppose a student includes two descriptions that are identical, such as "fish eat food", where one description is denoted using the word "interaction" and the other description is denoted using the words "role/purpose". Therefore, the interaction between the elements "fish" and "food" is recorded as "fish eat food" and the role/purpose of the element "fish" is recorded as "fish eat food".
7	If two (2) or more instances of the same interaction are drawn and/or described only one (1) instance of that interaction shall be recorded per drawing.	If a student draws multiple "fish" elements and connects them all to the element of "food" only one (1) instance of the "fish-food" interaction is recorded.
8	An interaction classified at the sensibility level is assigned a score of one (1). An interaction classified at the literacy level is assigned a score of two (2). An interaction classified at the capability level is assigned a score of three (3).	*For sensibility:* A line connecting the elements "fish" and "food". *For literacy:* A line connecting the elements of "fish" and "food" and the description "eating" which defines an action between the elements. *For capability:* A line connecting the elements of "fish" and "food" and the description "eats to get energy" which defines an action and a reaction between the elements.

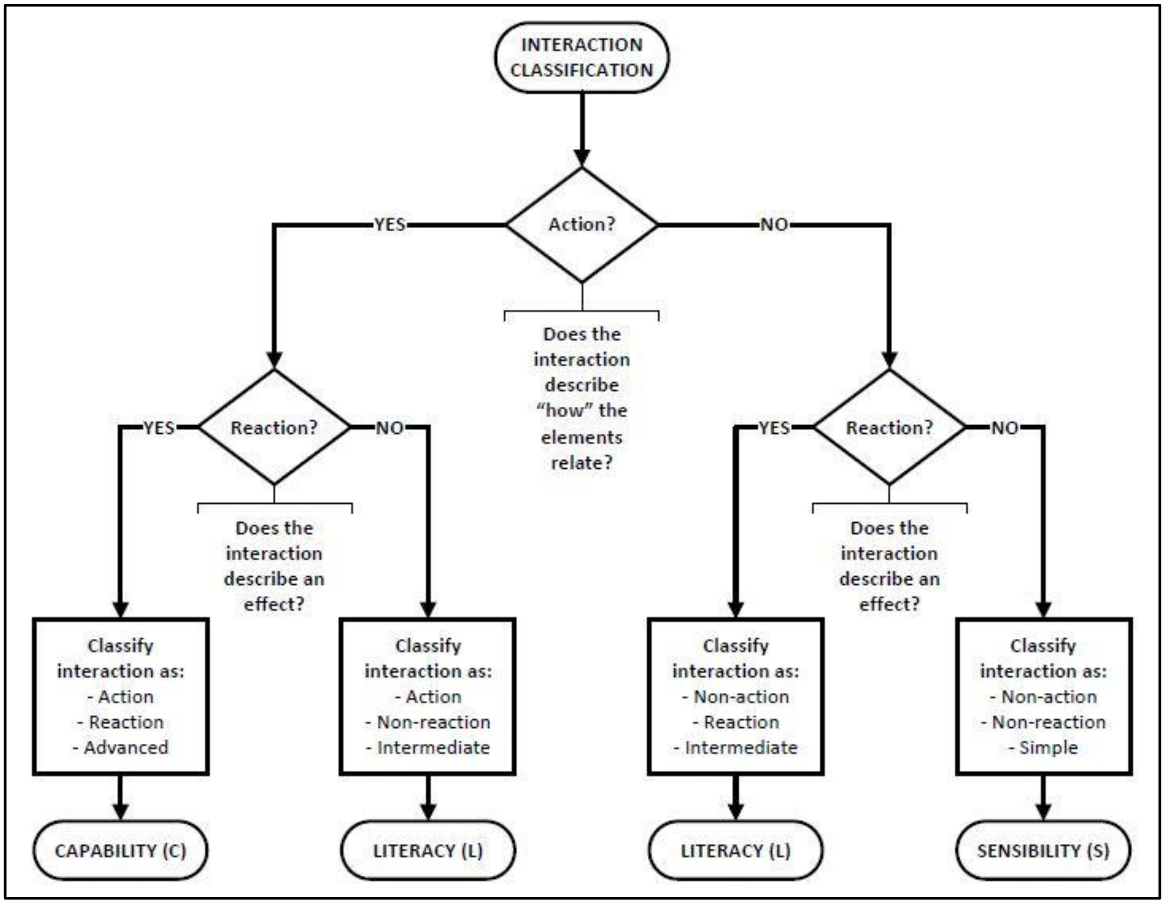

Figure 3-2: Interaction Classification Flowchart

3.2.3.3 Classifying Perspectives (Roles/Purposes)

The process of classifying perspectives meant classifying roles/purposes, which are the result of applying the systems thinking concept of perspectives. In the context of a fish-tank system, it would be conceivable to define all the possible roles/purposes for each element. However, defining all of these roles/purposes, like with interactions, is not realistic. Suppose that each of the forty-nine (49) elements defined in Table 8-1 in Appendix B: Element Classification Tables (which also includes at least one potential role/purpose for each element according to Mills (1987)) were assigned a role/purpose from each of the three systems thinking learning levels. This would result in three (3) roles/purposes per element meaning, at a minimum, 49*3 = 147 roles/purposes would need to be defined. Instead of defining an exhaustive list of all potential roles/purposes for each element, the classification structure developed for roles/purposes was based upon the simple patterns necessary to classify all potential roles/purposes that students could conceivably identify for a fish-tank system.

The simple patterns of roles/purposes were determined from the systems thinking concept of perspectives (P) within the DSRP framework from Cabrera (2006). Cabrera and Cabrera (2015) define perspectives fundamentally as "a point from which we are viewing and the thing or things that are in view" (p. 50). In other words, perspectives are a point-of-view or a lens through which a specific element in a system is viewed. There are many perspectives that could be applied for any given situation, but what if there were only three different levels of perspective-taking, one for each systems thinking learning level, that could apply to elements in a fish-tank system? Evidence to answer that question was drawn from a related study by Hmelo-Silver, Liu, Gray, and Jordan (2015) who defined five aquarium mental models to characterize student learning outcomes for aquatic systems. The first three of these mental models defined by Hmelo-Silver et al. (2015) characterize learning outcomes for perspectives that could be reasonably expected of learners in the initial learning phase of systems thinking. Drawing upon these three mental models informed the three patterns that were used to classify roles/purposes:

(1) The first pattern was drawn from the first mental model presented by Hmelo-Silver et al. (2015) called "egocentric". This mental model is characterized by adopting the perspective of an observer of a fish-tank system. In the case of this research study, the observer of the system was the student drawing the fish-tank system.
(2) The second pattern was drawn from the second mental model presented by Hmelo-Silver et al. (2015) called "simple healthy fish". This mental model is characterized by adopting the perspective of a fish in the fish-tank system. In other words, all roles/purposes for elements focus on helping the fish in some way.
(3) The third pattern was drawn from the third mental model presented by Hmelo-Silver et al. (2015) called "good tank". This mental model is characterized by

adopting the perspective of the fish-tank system as a whole. In other words, all roles/purposes for elements focus on helping the fish-tank system in some way.

The first pattern describes an individual's point-of-view of elements in a fish-tank system. This point-of-view sees elements through the lens that the role/purpose of each element is to enhance the observer's experience with the system (Hmelo-Silver et al., 2015). The second pattern describes an element's point-of-view of other elements in a fish-tank system. This point-of-view sees elements through the lens that the role/purpose of each element is related to other elements in the system. The third pattern was describes the system's point-of-view of elements in a fish-tank system. This point-of-view sees elements through the lens that the role/purpose of each element is related to the system as a whole. Therefore, classifications to distinguish individualistic roles/purposes, from elementalistic roles/purposes, from systemic roles/purposes were needed to fully define roles/purposes in a fish-tank system.The connections between the three patterns and the three classifications are summarized in Table 3-7.

Table 3-7: Role/Purpose Patterns and Role/Purpose Classifications

Pattern	Classification	Definition
(1) Observer's point-of-view of role/purpose	Individualistic Roles/Purposes	An individualistic role/purpose is viewed through the observer's own lens. In this situation, the observer views the role/purpose of an element in a system as it relates to them observing a fish-tank system. Examples: A fish is a pet; the rocks are for decoration.
(2) Element's point-of-view of role/purpose	Elementalistic Roles/Purposes	An elementalistic role/purpose is viewed through an element's lens. In this situation, the observer views the role/purpose of an element in a system as it relates to other elements in the fish-tank system. Example: The filter keeps the water clean.
(3) System's point-of-view of role/purpose	Systemic Roles/Purposes	A systemic role/purpose is viewed through the system's lens. In this situation, the observer views the role/purpose of an element in a system as it relates to the fish-tank system as a whole. Example: The aerator provides water circulation to keep the water from becoming stagnant.

Each of the three role/purpose classifications naturally align with one of the three systems thinking learning levels. An individualistic role/purpose resides at the sensibility level because this point-of-view only demonstrates an awareness that elements have a role or purpose, but this point-of-view is limited to the observer of the system. An elementalistic role/purpose resides at the literacy level because this point point-of-view demonstrates knowledge about how a specific element's role/purpose is related to other elements in the system, but this point-of-view is limited to the elements in the system. A systemic role/purpose resides at the capability level because this point-of-view demonstrates understanding about why a specific element exists in the system. The role/purpose classifications for each systems thinking learning level are summarized in Table 3-8.

Table 3-8: Role/Purpose Classifications and Systems Thinking Learning Levels

Learning Level	**Classification**	**Definition**
Sensibility	Individualistic Roles/Purposes	A role/purpose at the sensibility level demonstrates awareness that an element in a fish-tank system has a role or purpose, but that role/purpose is individualistically focused. Roles/purposes at this level are viewed from the observer's point-of-view of the fish-tank system.
Literacy	Elementalistic Roles/Purposes	A role/purpose at the literacy level demonstrates knowledge about the role/purpose of an element in a fish-tank system, but that role or purpose is elementalistically focused. Roles/purposes at this level are viewed from the element's point-of-view to explain how that role/purpose relates to other elements in the fish-tank system.
Capability	Systemic Roles/Purposes	A role/purpose at the capability level demonstrates understanding about the role/purpose of an element in a fish-tank system, but that role is systemically focused. Roles/purposes at this level are viewed from the system's point-of-view and explain why elements exist in the fish-tank system.

The classification structure could now be used to classify potential roles/purposes identified by students for a fish-tank system. The role/purpose classification flowchart used during the classification process is presented in Figure 3-3. While analyzing each drawing, roles/purposes were classified and recorded according to specific rules in preparation for the quantitative analysis. The rules used to classify and record roles/purposes are described in Table 3-9.

Table 3-9: Rules for Classifying and Recording Roles/Purposes

Rule #	**Rule Description**	**Example (if necessary)**
1	A role/purpose must be assigned to at least one (1) distinguishable element or system to be recorded.	The description “the tank is for holding everything” can be recorded as a role/purpose, whereas the statement “holds everything” cannot be recorded as a role/purpose unless the statement is assigned to a distinguishable element (see Rule #2).
2	A role/purpose must be written in words. A role/purpose can either be assigned as a written label connected to a distinguishable element using lines/arrows or as a written description next to a distinguishable element.	
3	A role/purpose must be labeled and/or described in a “distinguishable” manner to be recorded. A “distinguishable” role/purpose is recognizable or identifiable at first glance without extra effort.	
4	Only one (1) role/purpose shall be assigned to each element. If multiple roles/purposes are assigned to the same element, then only the role/purpose classified at the higher systems thinking learning level shall be recorded.	Suppose the element “fish” has been assigned both the role/purpose of “to swim around the tank” and “to be a pet”. Since the role/purpose of “to swim around the tank” is classified at a literacy level (from the element’s point-of-view), only this role/purpose shall be recorded for the element “fish”.

Rule #	Rule Description	Example (if necessary)
5	A label or description that includes the prepositions *to* or *for* or the pronoun *so* is always recorded as a role/purpose.	A line connecting the distinguishable element of "fish" to the description "to swim" is recorded as "the role/purpose of the fish is to swim". The description of "so fish can live" written next to the distinguishable element of "water" is recorded as "the role/purpose of water is so fish can live".
6	Descriptions that include the verbs *add, make, give, gave, get, got, keep, help, is, are, allow, or* provide are recorded as a role/purpose. Descriptions using other verbs are recorded as an interaction and not a role/purpose.	The description "the fish swims in the water" is recorded as an interaction. However, the description "the fish is swimming in the water" is recorded as a role/purpose because the linking verb "is" is used in the description.
7	A part of a drawing or a description that is recorded as a role/purpose cannot also be recorded as an interaction unless both a role/purpose and an interaction are distinguishable.	Suppose a student includes two descriptions that are identical, such as "fish eat food", where one description is denoted using the word "interaction" and the other description is denoted using the words "role/purpose". Therefore, the interaction between the elements "fish" and "food" is recorded as "fish eat food" and the role/purpose of the element "fish" is recorded as "fish eat food".
8	If two (2) or more instances of the same role/purpose are labeled or described only one (1) instance of that interaction shall be recorded per drawing.	If a student draws multiple "fish" elements and labels each with the description "fish make waste" only one instance of the role/purpose of a fish is to "make waste" is recorded.
9	A role/purpose classified at the sensibility level is assigned a score of one (1). A role/purpose classified at the literacy level is assigned a score of two (2). A role/purpose classified at the capability level is assigned a score of three (3).	*For sensibility:* "Rocks are decoration" is a role/purpose assigned to the element "rocks" from the observer's point-of-view. *For literacy:* "Rocks allow fish to hide" is a role/purpose assigned to the element "rocks" from the element's point-of-view. *For capability:* "The air pump helps circulate the water to improve tank and water health" is a role/purpose assigned to the element "pump" from the system's point-of-view.

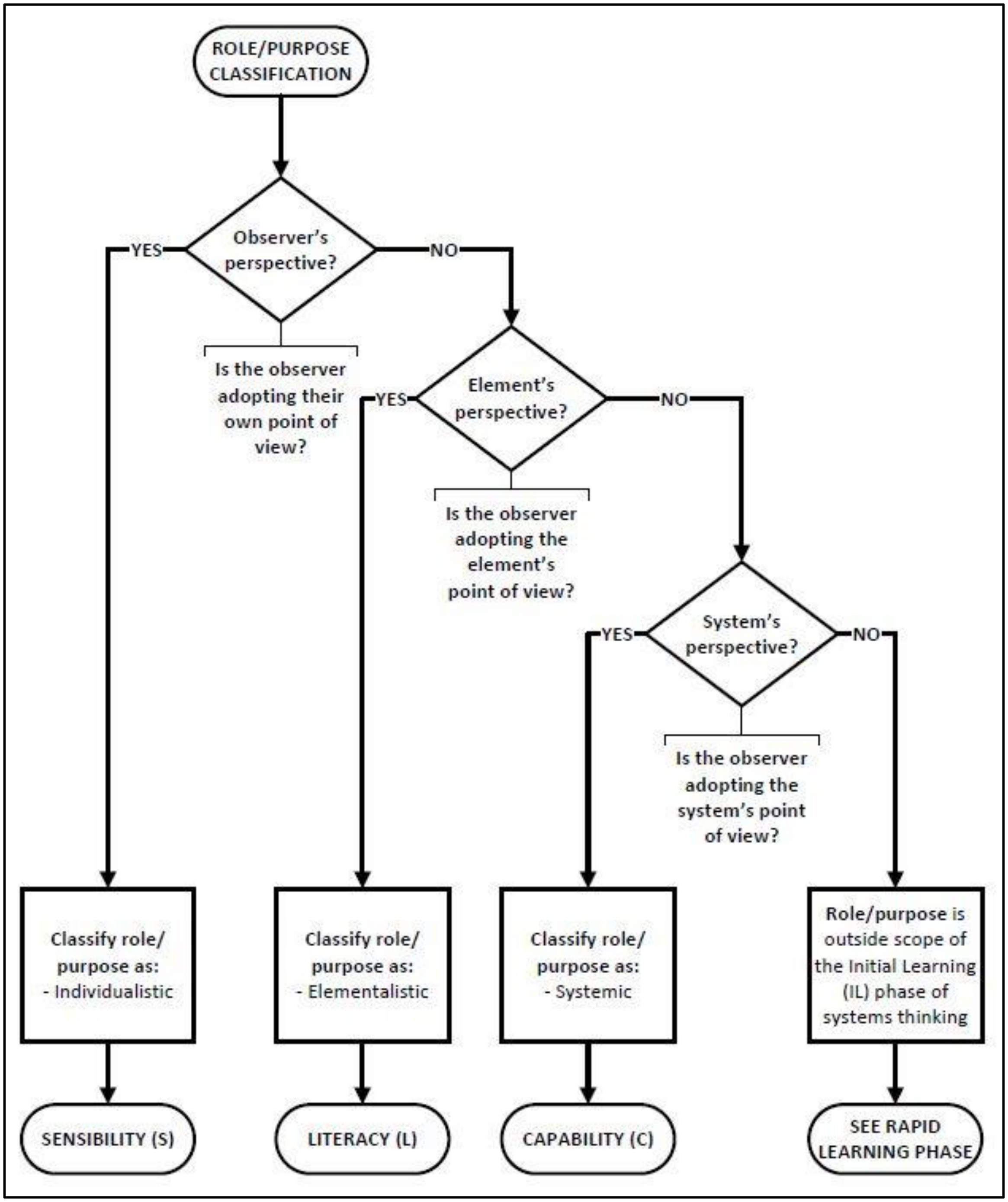

Figure 3-3: Role/Purpose Classification Flowchart

3.2.4 Inter-coder Agreement

An inter-coder agreement analysis was conducted for this research to determine the extent to which two independent coders reached the same conclusions about the contents of the fish-tank system drawings using the qualitative methodology described in section 3.2.3. This type of analysis is widely considered as a critical component for research methodologies that employ a content analysis and without this analysis, any resultant data cannot be considered valid (Lombard, Snyder-Duch, & Bracken, 2002). The index chosen to measure inter-coder agreement in this research was Krippendorff's Alpha because it accounted for chance agreements between coders and it was simple to calculate by hand using binary data from two coders with no missing data (Krippendorff, 2011). There is no established standard for the acceptable level of agreement for an inter-coder agreement analysis, but Neuendorf (2002) suggests that 90% or greater agreement "would be acceptable to all" and that 80% or greater agreement "would be acceptable in most situations" (p. 145). Therefore, for this research the minimum acceptable level of agreement between both coders was set at 80% or greater.

The inter-coder agreement analysis was conducted in three parts. The first part of the analysis was conducted following the design of the initial methodology for classifying the contents of the fish-tank system drawings. Inter-coder agreement was assessed informally with two independent coders who were trained to use the methodology and who each evaluated the same drawings from five (5) randomly selected students. Each student completed two drawings (Drawing A and Drawing B), therefore the two coders evaluated ten (10) total drawings. The total level of agreement for part one was only 68%. Since this result was less than the minimum accepted value of 80%, the methodology was refined following a debrief with both coders and the researcher to combine similar elements (for example: "filter tubes" and "filter" were combined to be just "filter") and clarify which verbs constituted whether a description was recorded as an interaction versus a role/purpose (for example: descriptions including the verbs *give*, *gave*, *got*, and *get* were miss-recorded as interactions when these descriptions should have been recorded as roles/purposes).

The second part of the analysis was conducted following the refinement of the methodology. Inter-coder agreement was assessed again with the same two independent coders who were trained to use the refined methodology and who each evaluated a new set of drawings from five (5) randomly selected students (ten (10) total drawings). The total level of agreement for part two improved to 83%. Since this result was greater than the minimum accepted value of 80%, this indicated that a larger sample of drawings could be evaluated to formally assess inter-coder agreement. After a debrief between both coders and the researcher, the methodology was refined again to combine similar elements (for example: “air” and “bubbles” were combined to be “air and/or bubbles”) and to add additional rules to simplify the number of interactions and roles/purposes that could be recorded (for example: if multiple roles/purposes were assigned to the same element, only the role/purpose that was classified at the higher learning level was recorded).

The third part of the analysis was conducted following the second refinement of the methodology. Inter-coder agreement was assessed again with the same two independent coders who were trained to use the refined methodology and who each evaluated a new set of drawings from twenty-five (25) randomly selected students (fifty (50) total drawings). This number was chosen because it accounted for over 25% of the ninety-seven (97) total students in the experiment which was determined to be an appropriate representative sample based on this sample size and the time required to evaluate each drawing. The total level of agreement for part three improved to 88%. Since this result was greater than the minimum accepted value of 80%, this indicated an agreement that “would be acceptable in most situations” (Neuendorf, 2002, p. 145). The results from the inter-coder agreement analysis are presented in Table 3-10 for all three parts in terms of each drawing (Drawing A and Drawing B) and combined (A + B) for elements (E), interactions (I), roles/purposes (R), and totals (T).

Table 3-10: Inter-Coder Agreement Results

Item Coded	**Part #1 (5 students; 10 drawings)**		**Part #2 (5 students; 10 drawings)**		**Part #3 (25 students; 50 drawings)**	
Elements (E)	A: 67% B: 74%	A + B: 70%	A: 88% B: 95%	A + B: 91%	A: 90% B: 93%	A + B: 91%
Interactions (I)	A: 100% B: 37%	A + B: 68%	A: 100% B: 73%	A + B: 87%	A: 96% B: 74%	A + B: 85%
Roles/Purposes (R)	A: 80% B: 50%	A + B: 65%	A: 100% B: 44%	A + B: 72%	A: 96% B: 80%	A + B: 88%
Totals (T)	A: 82% B: 53%	A + B: 68%	A: 96% B: 71%	A + B: 83%	A: 94% B: 82%	A + B: 88%

The results for each part of the analysis indicate a clear distinction between Drawing A and Drawing B. Inter-coder agreement for Drawing A was always less than inter-coder agreement for Drawing B for elements. This result is likely due to the increase in labeled elements in Drawing B compared to Drawing A, meaning students used a written label to identify a drawn element instead of only drawing an element, which likely increased inter-coder agreement in those cases. Conversely, inter-coder agreement for Drawing A was always greater than inter-coder agreement for Drawing B for interactions and roles/purposes. This result was likely due to the significant difference in the number and complexity of potential interactions that students drew in Drawing A compared to Drawing B. Students drew significantly less interactions and roles/purposes in Drawing A compared to Drawing B, meaning that there were less opportunities for the independent coders to disagree for these two concepts, which may have increased the inter-coder agreement for Drawing A.

The results also indicate that inter-coder agreement for interactions and roles/purposes for Drawing B were only able to reach 76% to 80%, which barely met (or did not meet) the minimum acceptable agreement value of 80%. This result was likely due to how the worksheets used in the experiment were designed to allow for open-ended drawings, meaning students could draw, label, or describe interactions and roles/purposes in a fish-tank system in any way they wanted. Compared to elements, which were more limited in number, the potential number of possible interactions and roles/purposes that could be drawn by students were less bounded which may have caused the inter-coder agreement to be decreased for these two concepts.

Final coding for all drawings was conducted by the researcher. For the drawings included in part one and part two of the inter-coder agreement analysis, each drawing was re-coded by the researcher using the finalized methodology (presented in section 3.2.3). For the drawings included in part three of the inter-coder agreement analysis, each drawing was coded according to the results from the two independent coders with any disagreements between the two coders decided by the researcher according to the finalized methodology. The remaining drawings not included in the inter-coder agreement analysis were coded by the researcher according to the finalized methodology. The results of the final coding for all drawings concluded the qualitative methods portion of the methodology and allowed for the data to be analyzed using the quantitative methods presented in the next section.

3.2.5 Quantitative Methods

The design of this research was based upon a content analysis which necessitated the use of both qualitative and quantitative methods to interpret the collected data (Leedy & Ormrod, 2016). The qualitative methods of the content analysis, including the development of the classification structures for each of the three systems thinking concepts (distinctions, relationships, and perspectives), were described in section 3.2.3. The classification structures were used to classify elements, interactions, and perspectives according to the three systems thinking learning levels (sensibility, literacy, and capability) and the frequencies of each were recorded for both collected drawings (Drawing A and Drawing B) for each student. In this section, the quantitative methods of the content analysis used to analyze the differences in recorded frequencies between both drawings for each concept and student are described. The three inferential statistical tests chosen to conduct the analysis were: 1) the two-sample t-test, 2) the paired comparison test, and 3) the Wilcoxon signed ranks test. The following three sections provide details about each test. For a list of the variables used in these tests, readers should refer to Table 9-1 in Appendix C: Glossary of Variables.

3.2.5.1 Two-Sample t-Test

The two-sample t-test is a statistical test used to draw inferences about the differences in means for a randomized design that involves sampling from two levels of a factor, where both levels are assumed to be from independent normal populations (Montgomery, 2013b) (see section 3.3.3 about data normality assumptions). The factor of interest for this statistical test was systems thinking learning and the levels corresponded to each of the fish-tank system drawings (Drawing A and Drawing B) that students were asked to complete during the experiment. y_{ij} was used to represent a sample from a systems thinking learning concept of interest for each i drawing [A, B] and j student. The values of n_A and n_B were equal to the sample sizes for each drawing and $\bar{y}_A$ and $\bar{y}_B$ were equal to the sample means for each drawing. With these variables established, the test statistic t_0 in Equation 3-1 was calculated to test for differences in the means of the two samples. The variable $S_p = \sqrt{S_p^2}$, where S_p^2 was calculated according to Equation 3-2 as an estimate of the common variance between the two individual samples each having sample variances of S_A^2 and S_B^2 (Montgomery, 2013b). The two-sample t-test assumes that the true variances of both samples are unknown but equal, which is a reasonable assumption if S_A^2 and S_B^2 are similar (see section 3.3.3 about equal variance assumptions).

Equation 3-1: Test Statistic for the Two-Sample t-Test

$$t_0 = \frac{\bar{y}_A - \bar{y}_B}{S_p\sqrt{\frac{1}{n_A} + \frac{1}{n_B}}}$$

Equation 3-2: Estimate of Common Variance between Drawing A and Drawing B

$$S_p^2 = \frac{(n_A - 1)S_A^2 + (n_B - 1)S_B^2}{n_A + n_B - 2}$$

To test whether the mean of Drawing B (μ_B) was greater than the mean of Drawing A (μ_A), a two-sided hypothesis test was conducted with the null (H_0) and alternative (H_1) hypotheses stated as: $H_0: \mu_A = \mu_B$ and $H_1: \mu_A \neq \mu_B$. H_0 was rejected only if $|t_0| > t_{\alpha/2, n_A+n_B-2}$ for a specified significance level α (Montgomery, 2013b). If H_0 was rejected, there was evidence to show that the means of the two drawings were different meaning that one-sided hypothesis tests needed to be conducted to determine whether the mean of Drawing A or Drawing B was greater.

The null and alternative hypotheses for the one-sided test to determine whether the mean of Drawing B was greater than Drawing A (or the left-tailed test) were stated as: $H_0: \mu_A \geq \mu_B$ and $H_1: \mu_A < \mu_B$. H_0 was rejected only if $t_0 < -t_{\alpha, n_A+n_B-2}$ for a specified significance level α (Montgomery, 2013b). If H_0 was rejected, there was evidence to show that the mean of Drawing B was greater than the mean of Drawing A. Alternatively, the null and alternative hypotheses for the one-sided test to determine whether the mean of Drawing A was greater than Drawing B (or the right-tailed test) were stated as: $H_0: \mu_A \leq \mu_B$ and $H_1: \mu_A > \mu_B$. H_0 was rejected only if $t_0 > t_{\alpha, n_A+n_B-2}$ for a specified significance level α (Montgomery, 2013b). If H_0 was rejected, there was evidence to show that the mean of Drawing A was greater than the mean of Drawing B. Conducting these hypothesis tests for the two-sample t-test provided evidence to conclude whether teaching the systems thinking concepts resulted in a greater number of and a greater score for elements, interactions, and roles/purposes drawn by students for Drawing B compared to Drawing A.

3.2.5.2 Paired Comparison Test

The paired comparison test (or paired t-test) is another statistical test used to draw inferences about the differences in two sample means, but this test uses a paired comparison design (Montgomery, 2013b). A paired comparison design is used when two tests are conducted on the same "specimen" to measure and compare the results. In this research, the specimens were the students and the two tests were the fish-tank system drawings (Drawing A and Drawing B) used to evaluate systems thinking learning. y_{ij} was defined as a sample from a systems thinking learning concept of interest for each *i* drawing [A, B, BA] and j student. Equation 3-3 was used to calculate the paired difference d_j for each student. Pairing these two samples assumes that the sample sizes for each drawing, n_A and n_B, are equal resulting in a paired sample size of n_{BA} where the subscript of *i* = BA is the paired difference between Drawing B and Drawing A.

Equation 3-3: Paired Difference between Drawings

$$d_j = y_{Bj} - y_{Aj} \quad for\ j = 1, 2, \dots, n_i$$

The paired comparison test was able to draw inferences about the difference in the means for the two drawings ($\mu_B - \mu_A$) by drawing inferences about the mean of the difference μ_d (Montgomery, 2013b). Therefore, the null hypothesis of $H_0\colon \mu_A = \mu_B$ for the two-sided test used in the two-sample t-test was equivalent to testing the null hypothesis of $H_0\colon \mu_d = 0$. For the two-sided test, the alternative hypothesis was stated as: $H_1\colon \mu_d \neq 0$. H_0 was rejected only if $|t_0| > t_{\alpha/2, n_{BA}-1}$ for a specified significance level α (Montgomery, 2013b). The test statistic t_0 was calculated according to Equation 3-4, where $\bar{d}$ was the sample mean of the differences and S_d, the sample standard deviation of the differences, was calculated according to Equation 3-5.

Equation 3-4: Test Statistic for the Paired Comparison Test

$$t_0 = \frac{\bar{d}}{S_d / \sqrt{n_{BA}}}$$

Equation 3-5: Sample Standard Deviation of the Differences

$$S_d = \left[\frac{\sum_{j=1}^{n_{BA}} d_j^2 - \frac{1}{n_{BA}}\left(\sum_{j=1}^{n_{BA}} d_j\right)^2}{n_{BA} - 1}\right]^{1/2}$$

If H_0 was rejected, there was evidence to show that the difference in means between the two drawings was not equal to zero (i.e. the means of the two drawings were different) meaning that one-sided hypothesis tests needed to be conducted to determine whether the mean of Drawing A or Drawing B was greater. The null and alternative hypotheses for the one-sided test to determine whether the difference in means were less than zero (or the left-tailed test) were stated as: $H_0: \mu_d \geq 0$ and $H_1: \mu_d < 0$. H_0 was rejected only if $t_0 < -t_{\alpha, n_{BA}-1}$ for a specified significance level α (Montgomery, 2013b). If H_0 was rejected, there was evidence to show that the difference in means were less than zero (i.e. the mean of Drawing A was greater than the mean of Drawing B). Alternatively, the null and alternative hypotheses for the one-sided test to determine whether the difference in means were greater than zero (or the right-tailed test) were stated as: $H_0: \mu_d \leq 0$ and $H_1: \mu_d > 0$. H_0 was rejected only if $t_0 > t_{\alpha, n_{BA}-1}$ for a specified significance level α (Montgomery, 2013b). If H_0 was rejected, there was evidence to show that the difference in means were greater than zero (i.e. the mean of Drawing B was greater than the mean of Drawing A).

The paired comparison test is similar to the two-sample t-test, but conducting this test eliminated the variability between students by blocking, or pairing, the two observations for each student (Montgomery, 2013b). This test offered additional evidence to determine whether teaching specific systems thinking concepts resulted in a greater number of and a greater score for elements, interactions, and roles/purposes drawn by students for Drawing B compared to Drawing A by analyzing the differences in samples instead of the samples individually.

3.2.5.3 Wilcoxon Signed Ranks Test

The Wilcoxon signed ranks test is a non-parametric statistical test used to draw inferences about differences in medians for situations where two samples can be paired (Conover, 1999). This test was similar to the paired comparison test presented in section 3.2.5.2, but it differs in that the paired differences for samples from Drawing A and Drawing B are used to determine whether the samples come from populations with the same median *and* mean. This test begins, similar to the paired comparison test, with the calculation of the paired difference $d_j = y_{Bj} - y_{Aj}$ where y_{ij} is defined as a sample from a systems thinking learning concept of interest for each *i* drawing [A, B, BA] and *j* student (see Equation 3-3). Unlike the paired comparison test, however, the Wilcoxon signed ranks test, since it is a nonparametric test, does not assume an underlying population probability distribution. Instead, this test assumes that the distribution of paired differences is symmetric (Conover, 1999). This assumption allows for inferences about the mean to be drawn because it coincides with the median in a symmetric distribution. Although the assumption of symmetry is not as strong as the assumption of normality found in the paired comparison test, this test is valid for situations where the underlying probability distribution is unknown or cannot be reasonably assumed as normal (Conover, 1999) (see section 3.3.3 about data normality assumptions).

The test statistic for this test was calculated by determining ranks from the paired differences of $(y_{Aj},\ y_{Bj})$. Paired differences equal to zero (for the case when $y_{Aj} = y_{Bj}$ or $d_j = 0$) were omitted from the calculation of the test statistic. Ranks were assigned to the remaining d_j from 1 to $n_{BA}{}'$ (where $n_{BA}{}'$ = the number of pairs remaining after omitting the pairs equal to 0) based on the magnitude of the absolute differences $|d_j|$. The rank of 1 was assigned to the pair with the smallest absolute difference and the rank of $n_{BA}{}'$ was assigned to the pair with the largest absolute difference. If any ties occurred between pairs (i.e. two or more pairs had the same absolute difference), then according to Conover (1999), "assign to each of these pairs the *average* of the ranks that would have otherwise been assigned" (p. 352-353). For example, if the ranks of 10, 11, and 12 were to be assigned to three tied pairs, then each pair was assigned the average rank of $\left(\frac{1}{3}\right) * (10 + 11 + 12) = \left(\frac{1}{3}\right) * (33) = 11$. Once the ranking of each pair was complete, R_j was used to denote either the rank assigned to $(y_{Aj},\ y_{Bj})$ if $d_j > 0$ (i.e. a positive difference) or the negative of the rank assigned to $(y_{Aj},\ y_{Bj})$ if $d_j < 0$ (i.e. a negative difference). Since the sample size n_{BA}

> 50 for this research, the normal approximation was used to calculate the test statistic T shown in Equation 3-6 (Conover, 1999).

Equation 3-6: Normal Approximation of Test Statistic for Wilcoxon Signed Ranks Test

$$T = \frac{\sum_{j=1}^{n_{BA}'} R_j}{\sqrt{\sum_{j=1}^{n_{BA}'} R_j^2}}$$

To test whether the difference in medians and means between Drawing A and Drawing B were equal to zero, the two-sided null and alternative hypotheses were stated in terms of the expected value of the paired difference (d) as: $H_0: E(d) = 0$ and $H_1: E(d) \neq 0$. H_0 was rejected for a specific significance level α if $|T| > z_{1-\alpha/2}$, where z was determined from a cumulative standard normal distribution. If H_0 was rejected, there was evidence to show that the expected value for the difference in medians and means between the two drawings was not equal to zero (i.e. the medians and means of the two drawings were different) meaning that one-sided hypothesis tests needed to be conducted to determine whether the median and mean of Drawing A or Drawing B was greater.

The null and alternative hypotheses for the one-sided test to determine whether the difference in medians and means were less than zero (or the left-tailed test) were stated as: $H_0: E(d) \geq 0$ and $H_1: E(d) < 0$ where H_0 was rejected for a specific significance level α if $T < -z_{1-\alpha}$. If H_0 was rejected, there was evidence to show that the expected value for the difference in medians and means were less than zero (i.e. the median and mean of Drawing A was greater than the median and mean of Drawing B). Alternatively, the null and alternative hypotheses for the one-sided test to determine whether the difference in medians and means were greater than zero (or the right-tailed test) were stated as: $H_0: E(d) \leq 0$ and $H_1: E(d) > 0$ where H_0 was rejected for a specific significance level α if $T > z_{1-\alpha}$. If H_0 was rejected, there was evidence to show that the expected value for the difference in medians and means were greater than zero (i.e. the median and mean of Drawing B was greater than the median and mean of Drawing A).

Although this test was similar to both the two-sample t-test and the paired comparison test, the inferences drawn from this test did not rely on the assumption of normality which may not have been a valid assumption for the populations included in this research (see section 3.3.3 for normality assumptions). Therefore, this test offered evidence from a non-parametric statistics perspective to determine whether teaching specific systems thinking concepts resulted in a greater number of and a greater score for elements, interactions, and roles/purposes drawn by students for Drawing B compared to Drawing A.

3.2.6 Testable Hypotheses

The four research questions and corresponding research hypotheses presented in sections 1.3 and 1.4 respectively are restated here in pairs for convenience:

(1) *First Question:* Is there a statistically significant difference between the elements identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of distinctions?
   - *First Hypothesis:* There is a statistically significant difference between the elements identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of distinctions.

(2) *Second Question:* Is there a statistically significant difference between the interactions identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of relationships?
   - *Second Hypothesis:* There is a statistically significant difference between the interactions identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of relationships.

(3) *Third Question:* Is there a statistically significant difference between the roles/purposes identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of perspectives?
   - *Third Hypothesis:* There is a statistically significant difference between the roles/purposes identified by non-experts in a fish-tank system drawing

before and after learning about the systems thinking concept of perspectives.

(4) *Fourth Question:* Is there a statistically significant difference between the totals of elements, interactions, and roles/purposes identified by non-experts in a fish-tank system drawing before and after learning about the three systems thinking concepts of distinctions, relationships, and perspectives?

- *Fourth Hypothesis:* There is a statistically significant difference between the totals of elements, interactions, and roles/purposes identified by non-experts in a fish-tank system drawing before and after learning about the three systems thinking concepts of distinctions, relationships, and perspectives.

To answer these questions and address the corresponding hypotheses, each question-hypothesis pair was translated into a testable hypothesis based on the qualitative and quantitative methodologies covered in the previous sections. The testable hypotheses for each general question-hypothesis pair, and for each statistical test, are presented in Table 3-11 in the form of a two-sided hypothesis test. For a glossary of variables used in the testable hypotheses, readers should refer to Table 9-1 in Appendix C: Glossary of Variables.

Table 3-11: Testable Hypotheses

General Question-Hypothesis Pair	Testable Hypothesis for Number (x)	Testable Hypothesis for Score (z)	Statistical Test
(1) Distinctions - Elements (E)	$H_0: \mu_{x_{AE}} = \mu_{x_{BE}}$ $H_1: \mu_{x_{AE}} \neq \mu_{x_{BE}}$	$H_0: \mu_{z_{AE}} = \mu_{z_{BE}}$ $H_1: \mu_{z_{AE}} \neq \mu_{z_{BE}}$	Two-Sample t-Test (section 3.2.5.1)
	$H_0: \mu_{d_{x_E}} = 0$ $H_1: \mu_{d_{x_E}} \neq 0$	$H_0: \mu_{d_{z_E}} = 0$ $H_1: \mu_{d_{z_E}} \neq 0$	Paired Comparison Test (section 3.2.5.2)
	$H_0: E(d_{x_E}) = 0$ $H_1: E(d_{x_E}) \neq 0$	$H_0: E(d_{z_E}) = 0$ $H_1: E(d_{z_E}) \neq 0$	Wilcoxon Signed Ranks Test (section 3.2.5.3)
(2) Relationships - Interactions (I)	$H_0: \mu_{x_{AI}} = \mu_{x_{BI}}$ $H_1: \mu_{x_{AI}} \neq \mu_{x_{BI}}$	$H_0: \mu_{z_{AI}} = \mu_{z_{BI}}$ $H_1: \mu_{z_{AI}} \neq \mu_{z_{BI}}$	Two-Sample t-Test (section 3.2.5.1)
	$H_0: \mu_{d_{x_I}} = 0$ $H_1: \mu_{d_{x_I}} \neq 0$	$H_0: \mu_{d_{z_I}} = 0$ $H_1: \mu_{d_{z_I}} \neq 0$	Paired Comparison Test (section 3.2.5.2)
	$H_0: E(d_{x_I}) = 0$ $H_1: E(d_{x_I}) \neq 0$	$H_0: E(d_{z_I}) = 0$ $H_1: E(d_{z_I}) \neq 0$	Wilcoxon Signed Ranks Test (section 3.2.5.3)
(3) Perspectives - Roles/ Purposes (R/P)	$H_0: \mu_{x_{AR}} = \mu_{x_{BR}}$ $H_1: \mu_{x_{AR}} \neq \mu_{x_{BR}}$	$H_0: \mu_{z_{AR}} = \mu_{z_{BR}}$ $H_1: \mu_{z_{AR}} \neq \mu_{z_{BR}}$	Two-Sample t-Test (section 3.2.5.1)
	$H_0: \mu_{d_{x_R}} = 0$ $H_1: \mu_{d_{x_R}} \neq 0$	$H_0: \mu_{d_{z_R}} = 0$ $H_1: \mu_{d_{z_R}} \neq 0$	Paired Comparison Test (section 3.2.5.2)
	$H_0: E(d_{x_R}) = 0$ $H_1: E(d_{x_R}) \neq 0$	$H_0: E(d_{z_R}) = 0$ $H_1: E(d_{z_R}) \neq 0$	Wilcoxon Signed Ranks Test (section 3.2.5.3)
(4) Totals (T)	$H_0: \mu_{x_{AT}} = \mu_{x_{BT}}$ $H_1: \mu_{x_{AT}} \neq \mu_{x_{BT}}$	$H_0: \mu_{z_{AT}} = \mu_{z_{BT}}$ $H_1: \mu_{z_{AT}} \neq \mu_{z_{BT}}$	Two-Sample t-Test (section 3.2.5.1)
	$H_0: \mu_{d_{x_T}} = 0$ $H_1: \mu_{d_{x_T}} \neq 0$	$H_0: \mu_{d_{z_T}} = 0$ $H_1: \mu_{d_{z_T}} \neq 0$	Paired Comparison Test (section 3.2.5.2)
	$H_0: E(d_{x_T}) = 0$ $H_1: E(d_{x_T}) \neq 0$	$H_0: E(d_{z_T}) = 0$ $H_1: E(d_{z_T}) \neq 0$	Wilcoxon Signed Ranks Test (section 3.2.5.3)

3.3 Collection and Treatment of Data

In this section the methods for how data was collected and treated are presented.

3.3.1 Data Collection

Data was collected for this research using an experiment conducted during a pre-existing two-day event hosted by the Science and Math Investigative Learning Experiences (SMILE) Program on the Oregon State University (OSU) campus in Corvallis, Oregon. Since this research was conducted with human subjects, the research protocol was submitted to and approved by the OSU Human Research Protection Program (HRPP) and Institutional Review Board (IRB) prior to data collection under the study number IRB-2019-0090 (see section 10.1 and section 10.2 in Appendix D: Research Study Documents). The first day of the experiment was the SMILE High School Challenge on Friday April 26, 2019. The second day of the experiment was the SMILE Middle School Challenge on Saturday April 27, 2019. During both days students participated in a systems thinking workshop. This workshop was conducted with nine (9) groups of students over two days and served as the experiment to collect data for this research in the form of fish-tank system drawings. On April 26, 2019 the systems thinking experiment was conducted with five (5) groups of high school students during the SMILE High School Challenge. On April 27, 2019 the systems thinking experiment was conducted with four (4) groups of middle school students during the SMILE Middle School Challenge. The experiments were conducted by two members of the research study team (Instructor #1 and Instructor #2). The experiments did not vary between groups or differ for middle school versus high school students except for the instructor. The data collection matrix that details which groups were taught by each instructor for each day of the experiment is presented in Table 3-12. Also detailed in the table is the number of expected students who would participate in the experiment for each group.

Table 3-12: Data Collection Matrix

Systems Thinking Experiment – Day 1 (Fri. April 26, 2019) High School (HS)	HS Group #1	~ 20 students per group ~ 100 students total	Instructor #1 & Instructor #2
	HS Group #2		Instructor #1
	HS Group #3		Instructor #2
	HS Group #4		Instructor #1
	HS Group #5		Instructor #2
Systems Thinking Experiment – Day 2 (Sat. April 27, 2019) Middle School (MS)	MS Group #1	~ 25 students per group ~ 100 students total	Instructor #1
	MS Group #2		Instructor #2
	MS Group #3		Instructor #1
	MS Group #4		Instructor #2

For each group, the instructors used presentation slides to guide the experiment (see section 10.6 in Appendix D: Research Study Documents). The experiment began with an introduction to the instructors, a brief introduction to systems thinking, and an overview of the experiment. During the overview of the experiment, the instructors provided students with details about the experiment and allowed enough time for students to decide whether or not they wanted to participate in the experiment which was done to comply with OSU HRPP and IRB protocol. All students were provided with an assent form (see section 10.4 in Appendix D: Research Study Documents) and were asked to sign the form if they decided not to participate in the experiment. However, if a student signed the assent form this did not preclude that student from participating in the systems thinking workshop. Once the experiment overview was complete, the students were asked to draw a fish-tank system drawing (Drawing A). Students were presented with the problem statement that the water in the fish tank was turning green and asked to consider elements, interactions, and roles/purposes while completing their drawing. This first drawing of a fish-tank system served as a warm-up activity to evaluate systems thinking learning before the experiment. Students were given approximately five (5) minutes to complete Drawing A.

In the next part of the experiment, students were asked to answer two background questions about their prior knowledge of fish tanks. Then, the instructors transitioned to a lesson about the systems thinking concepts of distinctions, relationships, and perspectives, beginning with an overview of the three concepts. The first concept that the instructors taught was distinctions which was taught as the skill of identifying elements. After teaching the students about distinctions, the instructors presented the students with the same problem statement as in Drawing A and asked the students to start a new fish-tank system drawing (Drawing B) and draw and label elements. This process was repeated for the other two concepts of relationships and perspectives. For relationships, students were taught the skill of identifying interactions and asked to draw and label interactions in their fish-tank system drawing (Drawing B). For perspectives, students were taught the skill of identifying roles/purposes and asked to draw and label roles/purposes in their fish-tank system drawing (Drawing B). Students were given approximately three to four (3-4) minutes to complete their drawing for each concept. With any remaining time, the instructors concluded the experiment by facilitating a discussion to help students reflect on the concepts taught. At the conclusion of the experiment, students were asked to submit their drawings to the instructors. The worksheets that were provided to students to complete their drawings are shown in section 10.5 in Appendix D: Research Study Documents.

3.3.2 Treatment of Data

The data (Drawings A and B) were collected after each group completed the systems thinking experiment and stored until all groups had completed the experiment. The data for each group were then sorted into two sub-groups. The first sub-group for each group contained all data that did not have either a signed assent form by the student or a signed consent form from a parent (see section 10.1 in Appendix D: Research Study Documents for the consent form). Data without a signature on either of these forms meant the student and their parent(s) gave permission to include the student's drawing in this research. The second sub-group for each group contained all data that did have either a signed assent form by the student or a signed consent form from a parent. The data sorted into the second sub-group (including assent forms) were destroyed as per the IRB protocol since assent and/or was not provided to use that data in this research.

The data (Drawings A and B) sorted into the first sub-group were then separated from the accompanying assent form. All assent forms were destroyed as per the IRB protocol to ensure no data could be linked to a specific student. Using a random code generator, each student was assigned a five-digit code which was written on the physical copy of both Drawing A and Drawing B. These codes helped identify which group the student and their drawings were included in during the experiment. After all data were assigned a code, the physical data was shuffled to randomize the students and groups and then scanned to create an electronic copy. This electronic copy of the data was stored on a secure, cloud-based server by the Principal Investigator specified in the IRB protocol. The physical copies were kept securely stored except when used during the analysis.

3.3.3 Checking Data Sampling Assumptions

The two-sample t-test and the paired comparison test presented in section 3.2.5 rely on the assumptions that data samples are randomly collected, are from independent populations, and can be described by normal distributions (Montgomery, 2013b). The first assumption that data samples were randomly collected can be accepted since students in the experiment were randomly assigned to each group except for the fact that groups were defined as having all middle school students or all high school students.

The second assumption that data samples were collected from two independent populations can also be accepted. Each student was independent of other students, although, since Drawing A and Drawing B were collected from the same student, it would appear that these two sample populations are not independent. However, the samples for Drawing B were drawn after an intervention has occurred (i.e. the students were taught about systems thinking concepts). This intervention only affected how students thought about fish tanks and did not affect the prior knowledge students had about fish tanks. Therefore, it is reasonable to accept the assumption that students in Drawing A were independent of the students in Drawing B.

The third assumption that data samples were collected from an underlying normal distribution could not be accepted without checking for normality using normal probability plots. A normal probability plot is a simple graphical tool for checking whether data is normally distributed (Montgomery, 2013b). A plot was created for both Drawing A and Drawing B for elements, interactions, roles/purposes, and totals. This resulted in four (4) plots per drawing and eight (8) total plots, which are presented in Appendix E: Normal Probability Plots. The general procedure for creating the plots began with ranking the sample observations from smallest to largest. Then, the ordered samples were plotted against the observed cumulative frequency calculated using the expression $(j - 0.5)/n_i$, where j is the ordered sample number and n_i is the number of samples for drawing i [A, B]. For example, if a value of 10 is ordered sample number j = 53 and $n_i = 97$, then the observed cumulative frequency is $= (j - 0.5)/n_i = (53 - 0.5)/97 = 0.541$. If the normal distribution adequately describes the plotted data, then the plotted points will lie approximately along a straight line (which is always a subjective determination) or the calculated p-value will be greater than a specified significance level α (Montgomery, 2013b).

Based on the normal probability plots created for the data samples in this research, the number of elements and totals for both Drawing A and B appear visually to be well approximated by a normal distribution. However, the p-values for both plots are < 0.002 which is less than the significance level α of 0.05. Additionally, the plots for interactions and roles/purposes for both Drawing A and B do not appear visually to be well approximated by a normal distribution and the p-values for all plots are < 0.001 which is less than the significance level α of 0.05. Therefore, based on p-values it is not reasonable to accept the assumption that the data for elements, interactions, roles/purposes, and totals for both Drawing A and B are samples from normally distributed populations. These findings support the inclusion of the Wilcoxon signed ranks test (a non-parametric statistical test) which does not assume an underlying distribution. Although the normal probability plots are not conclusive in confirming normality, the inclusion of both types of hypothesis tests in this research provided multiple perspectives from which to evaluate the research questions.

3.4 Methodological Issues

In this section the five methodological issues of reliability, validity, replicability, bias, and representativeness related to this research are presented.

3.4.1 Reliability

The reliability of this research relates to the measurement instrument (the systems thinking experiment using a fish-tank drawing) and the qualitative data analysis. The reliability of the measurement instrument applies to how the experiment was administered to each group and whether the experiment was administered consistently. To address this, the experiment was standardized to reduce any inconsistencies that might result between groups. Additionally, both researchers who conducted the activity were highly knowledgeable about the systems thinking concepts that were presented and both researchers were trained together on how to conduct the activity to ensure consistency between groups. To address the reliability of the data, an inter-coder agreement analysis was conducted for 25% of the data (see section 3.2.4). This analysis resulted in a final overall inter-coder agreement of 88% between two independent coders which met the minimum accepted agreement value of 80% meaning the results "would be acceptable in most situations" (Neuendorf, 2002, p. 145). Conducting this analysis also resulted in a more robust and consistent methodology with examples and clear and concise rules for classifying and recording the data during the content analysis.

3.4.2 Validity

The validity of this research relates to both internal and external validity. The internal validity of the research experiment is the extent to which "accurate conclusions about cause-and-effect relationships within the data" can be drawn (Leedy & Ormrod, 2016, p. 85). To ensure internal validity many experimental factors were kept constant, including: all students were affiliated with the SMILE Program; all students were high school students on the first day of the experiment and all students were high school students on the second day of the experiment; the presentation of systems thinking information was standardized between all groups; and, the students in each group were randomly assigned.

The external validity of the research experiment is the extent to which the "results apply to situations beyond the study itself – in other words, the extent to which the conclusions drawn can be *generalized* to other contexts" (Leedy & Ormrod, 2016, p. 87). To ensure external validity the experiment was conducted in a classroom setting during a pre-existing workshop in order to replicate a "real-life" setting and the students who participated in the experiment were randomly selected from the SMILE Program student population. Additionally, an inter-coder agreement analysis was conducted (also discussed for reliability and presented in section 3.2.4) to ensure the conclusions drawn from this research can be used and trusted in future research.

3.4.3 Replicability

The methodology presented in this research sufficiently details how other researchers may replicate the findings from this research. Although this research was conducted with students in a specific context, the methodology described is general enough to be replicated in other contexts for different student populations.

3.4.4 Bias

According to Leedy and Ormrod (2016, p. 168-170), there are four categories of bias – sampling, instrumentation, response, and researcher bias. Sampling and instrumentation bias during the data collection portion of this research were minimized by conducting the experiment with randomized groups and by standardizing the presentation of the systems thinking experiment for each group. However, the design of the worksheets for the systems thinking experiment may have biased students during Drawing B to think of a fish-tank system as having a rectangular tank since this was already printed on the worksheet. In comparison, students completed Drawing A on a blank sheet of paper. Although this may not have had an effect on the rest of Drawing B, some students may not have labeled the fish tank as an element in their drawing. This potential source of bias was eliminated by giving every student "credit" for the fish tank as an element in Drawing B.

Response and researcher bias during the data analysis portion of this research were minimized by standardizing the presentation of the systems thinking experiment for each group and by creating robust operational definitions in the methodology to classify and record data during the content analysis as a result of an inter-coder agreement analysis conducted with two independent coders. Although only 25% of the data was coded by the two independent coders, the finalized methodology was more robust after conducting this analysis which resulted in more consistent results for the remaining 75% of the data coding performed by the researcher. A source of potential response bias could be found for the student responses to the question of “what is your familiarity of fish tanks?” during the experiment. This question may exhibit response bias by students because of the self-report nature of the question and the influence of students’ prior experiences with and knowledge about fish tanks (see section 4.3.1 for a more detailed analysis of this question).

3.4.5 Representativeness

Students who participated in this research were randomly sampled from the greater SMILE Program student population. Because students in SMILE do not represent the larger population of students, the results of this research cannot be used to represent all student populations, only SMILE students. However, as discussed for replicability, the methodology described herein, if applied to another context, is general enough to be used to measure systems thinking learning for other student populations.

3.5 Research Constraints

Two types of constraints which affected the experimental design of this research were identified. The first constraint was related to the structure of the SMILE Challenge Events where the experiment took place. Due to this constraint, no control group could be used because the SMILE Program expected that all students at the events would participate in the systems thinking workshop in order to learn about systems thinking concepts. This constraint also limited the measurement of expected student learning attributable to the repeated task of drawing a fish-tank system. Additionally, due to this constraint the time allotted for the experiment was limited to approximately forty-five (45) minutes and the group sizes were fixed at twenty to twenty-five (20-25) students. This constrained the design of the experiment to be successfully completed in that timeframe and also to be accommodating of the high number of students in one group. The second constraint was related to the human-subject testing requirements set by the IRB to protect the rights and welfare of the participants in the research experiment. Due to this constraint, not all students who participated in the systems thinking activity provided their assent to include their drawings as data in this research. This resulted in the omission of forty-six (46) drawings as data for this research due to a lack of assent provided.

Chapter 4
4 Results

4.1 Introduction

In this chapter, the results of the experiment are presented according to the methodology described in the previous chapter. The results are presented in two sections. In section 4.2, the results of the statistical tests described in the methodology to test each hypothesis are presented. In section 4.3, the exploratory results related to the experiment are presented. The results presented in both sections are based on the analysis of ninety-seven (97) students who participated in the experiment, completed both Drawing A and Drawing B of a fish-tank system, and provided their assent to include their drawings in this research. An additional fifty (50) students participated in the experiment, but these students either did not complete both drawings or did not provide assent, meaning these students were not included in the analysis. Therefore, the number of pairs of drawings included in the analysis and results was $n_A = n_B = n_{BA} = 97$.

4.2 Research Study Results

In this section, the results of the experiment are presented in the following order of systems thinking concepts: 1) distinctions (elements) in section 4.2.1, 2) relationships (interactions) in section 4.2.2, 3) perspectives (roles/purposes) in section 4.2.3, and 4) totals in section 4.2.4. For each concept, the results are presented in the following order of statistical tests: 1) two-sample t-test, 2) paired comparison test, and 3) Wilcoxon signed ranks test. For a list of the variables used in the results, readers should refer to Table 9-1 in Appendix C: Glossary of Variables.

4.2.1 Distinctions (Elements) Results

In this section, the results of the elements analysis are presented. The tabulated results for elements that were used to conduct the statistical tests are presented in Table 12-1 in Appendix F: Tabulated Results. During the analysis, eleven (11) additional, relevant elements drawn by students for a fish-tank system were identified, classified, and recorded according to the methodology described in section 3.2.3.1. The descriptions and classifications for each of these eleven (11) additional, relevant elements are presented in Table 8-3 and Table 8-4 respectively in Appendix B: Element Classification Tables.

4.2.1.1 Two-Sample t-Test Results for Elements

The purpose of the two-sample t-test was to determine whether there was a statistically significant difference between the mean number and the mean score for elements identified by students for Drawing A and Drawing B, and whether the mean number and the mean score for elements was greater for Drawing A or Drawing B. The results of the two-sample t-tests for elements are presented in Table 4-1.

Table 4-1: Two-Sample t-Test Results for Elements

Drawing	**E for [S]**		**E for [L]**		**E for [C]**		**x of E**			**z of E**		
	$\bar{x}_{ES}$	$\tilde{x}_{ES}$	$\bar{x}_{EL}$	$\tilde{x}_{EL}$	$\bar{x}_{EC}$	$\tilde{x}_{EC}$	$\bar{x}_{ET}$	$\tilde{x}_{ET}$	$S_{x_{ET}}$	$\bar{z}_{ET}$	$\tilde{z}_{ET}$	$S_{z_{ET}}$
A $n_A = 97$	2.47	3	2.97	3	0.19	0	5.63	5	2.38	8.97	8	4.80
B $n_B = 97$	2.92	3	4.73	4	0.63	0	8.28	8	2.57	14.27	13	5.56

Test	H_0	S_p^2	α	$t_{critical}$	t_0	***p-value***
2T (x)	$\mu_{x_{AE}} = \mu_{x_{BE}}$	6.14	0.05	1.97	-7.45	< 0.001
2T (z)	$\mu_{z_{AE}} = \mu_{z_{BE}}$	27.01	0.05	1.97	-7.10	< 0.001
LT (x)	$\mu_{x_{AE}} \geq \mu_{x_{BE}}$	6.14	0.05	1.65	-7.45	< 0.001
LT (z)	$\mu_{z_{AE}} \geq \mu_{z_{BE}}$	27.01	0.05	1.65	-7.10	< 0.001
RT (x)	$\mu_{x_{AE}} \leq \mu_{x_{BE}}$	6.14	0.05	1.65	-7.45	> 0.999
RT (z)	$\mu_{z_{AE}} \leq \mu_{z_{BE}}$	27.01	0.05	1.65	-7.10	> 0.999

Since $|t_0| > t_{\alpha/2,n_A+n_B-2}$ for the two-tailed (2T) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence to conclude that the mean number and the mean score for elements identified by students between Drawing A and Drawing B are different. Additionally, since $t_0 < -t_{\alpha,n_A+n_B-2}$ for the left-tailed (LT) test with a p-value < 0.001 and since $t_0 < t_{\alpha,n_A+n_B-2}$ for the right-tailed (RT) test with a p-value >

0.999 at a significance level α of 0.05, there is statistical evidence to conclude that the mean number and the mean score for elements identified by students in Drawing B is greater than Drawing A.

4.2.1.2 Paired Comparison Test Results for Elements

The purpose of the paired comparison test was to determine whether the mean of the paired differences between Drawing A and Drawing B for the number and the score for elements identified by students were statistically significant, and whether the difference between the two drawings was greater or less than zero (i.e. whether the number and the score for elements was greater for Drawing A or Drawing B). The results of the paired comparison tests for elements are presented in Table 4-2.

Table 4-2: Paired Comparison Test Results for Elements

Draw-ing	**E for [S] Difference**		**E for [L] Difference**		**E for [C] Difference**		**x of E Difference**			**z of E Difference**		
	$\bar{d}_{x_{ES}}$	$\tilde{d}_{x_{ES}}$	$\bar{d}_{x_{EL}}$	$\tilde{d}_{x_{EL}}$	$\bar{d}_{x_{EC}}$	$\tilde{d}_{x_{EC}}$	$\bar{d}_{x_{ET}}$	$\tilde{d}_{x_{ET}}$	$S_{d_{x_{ET}}}$	$\bar{d}_{z_{ET}}$	$\tilde{d}_{z_{ET}}$	$S_{d_{z_{ET}}}$
BA $n_{BA} = 97$	0.44	0	1.76	2	0.44	0	2.65	3	2.43	5.30	5	4.86

Test	H_0	S_d	α	$t_{critical}$	t_0	***p-value***
2T (x)	$\mu_{d_{x_E}} = 0$	2.43	0.05	1.98	10.75	< 0.001
2T (z)	$\mu_{d_{z_E}} = 0$	4.86	0.05	1.98	10.75	< 0.001
LT (x)	$\mu_{d_{x_E}} \geq 0$	2.43	0.05	1.66	10.75	> 0.999
LT (z)	$\mu_{d_{z_E}} \geq 0$	4.86	0.05	1.66	10.75	> 0.999
RT (x)	$\mu_{d_{x_E}} \leq 0$	2.43	0.05	1.66	10.75	< 0.001
RT (z)	$\mu_{d_{z_E}} \leq 0$	4.86	0.05	1.66	10.75	< 0.001

Since $|t_0| > t_{\alpha/2,n_{BA}-1}$ for the two-tailed (2T) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence to conclude that the mean of the paired differences between Drawing A and Drawing B for the number and the score for elements identified by students are different. Additionally, since $t_0 > -t_{\alpha,n_{BA}-1}$ for the left-tailed

(LT) test with a p-value > 0.999 and since $t_0 > t_{\alpha,n_{BA}-1}$ for the right-tailed (RT) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence to conclude that the mean of the paired differences for the number and the score for elements identified by students is greater than zero (i.e. the number and the score for elements in Drawing B is greater than Drawing A).

4.2.1.3 Wilcoxon Signed Ranks Test Results for Elements

The purpose of the Wilcoxon signed ranks test was to determine (from a non-parametric statistics perspective) whether the median and the mean of the paired differences between Drawing A and Drawing B for the number and the score for elements identified by students were statistically significant, and whether the difference between the two drawings was greater or less than zero (i.e. whether the number and the score for elements was greater for Drawing A or Drawing B). The results of the Wilcoxon signed ranks tests for elements are presented in Table 4-3.

Table 4-3: Wilcoxon Signed Ranks Test Results for Elements

Test	H_0	n_{BA}'	$\sum_{j=1}^{n_{BA}'} R_j$	$\sum_{j=1}^{n_{BA}'} R_j^2$	T	α	$z_{critical}$	***p-value***
2T (x)	$E(d_{x_E}) = 0$	81	3,106.00	178,749.00	7.35	0.05	1.96	< 0.001
2T (z)	$E(d_{z_E}) = 0$	86	3,454.00	215,209.00	7.45	0.05	1.96	< 0.001
LT (x)	$E(d_{x_E}) \geq 0$	81	3,106.00	178,749.00	7.35	0.05	1.64	> 0.999
LT (z)	$E(d_{z_E}) \geq 0$	86	3,454.00	215,209.00	7.45	0.05	1.64	> 0.999
RT (x)	$E(d_{x_E}) \leq 0$	81	3,106.00	178,749.00	7.35	0.05	1.64	< 0.001
RT (z)	$E(d_{z_E}) \leq 0$	86	3,454.00	215,209.00	7.45	0.05	1.64	< 0.001

Since $|T| > z_{1-\alpha/2}$ for the two-tailed (2T) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence (from a non-parametric statistics perspective) to conclude that the median and the mean of the paired differences between Drawing A and Drawing B for the number and the score for elements identified by students are different. Additionally, since $T > -z_{1-\alpha}$ for the left-tailed (LT) test with a p-value > 0.999 and since $T > z_{1-\alpha}$ for the right-tailed (RT) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence (from a non-parametric statistics perspective) to conclude that the mean of the paired differences for the number and the score for elements identified by students is greater than zero (i.e. the number and the score for elements in Drawing B is greater than Drawing A).

4.2.2 Relationships (Interactions) Results

In this section, the results of the interactions analysis are presented. The tabulated results for interactions that were used to conduct the statistical tests are presented in Table 12-2 in Appendix F: Tabulated Results.

4.2.2.1 Two-Sample t-Test Results for Interactions

The purpose of the two-sample t-test was to determine whether there was a statistically significant difference between the mean number and the mean score for interactions identified by students for Drawing A and Drawing B, and whether the mean number and the mean score for interactions was greater for Drawing A or Drawing B. The results of the two-sample t-tests for interactions are presented in Table 4-4.

Table 4-4: Two-Sample t-Test Results for Interactions

Drawing	**I for [S]**		**I for [L]**		**I for [C]**		**x of I**			**z of I**		
	$\bar{x}_{IS}$	$\tilde{x}_{IS}$	$\bar{x}_{IL}$	$\tilde{x}_{IL}$	$\bar{x}_{IC}$	$\tilde{x}_{IC}$	$\bar{x}_{IT}$	$\tilde{x}_{IT}$	$S_{x_{IT}}$	$\bar{z}_{IT}$	$\tilde{z}_{IT}$	$S_{z_{IT}}$
A $n_A = 97$	0.14	0	0.07	0	0.03	0	0.25	0	1.09	0.38	0	1.34
B $n_B = 97$	0.66	0	1.30	0	0.06	0	2.02	1	2.50	3.44	2	4.18

Test	H_0	S_p^2	α	$t_{critical}$	t_0	***p-value***
2T (x)	$\mu_{x_{AI}} = \mu_{x_{BI}}$	3.72	0.05	1.97	-6.40	< 0.001
2T (z)	$\mu_{z_{AI}} = \mu_{z_{BI}}$	9.63	0.05	1.97	-6.87	< 0.001
LT (x)	$\mu_{x_{AI}} \geq \mu_{x_{BI}}$	3.72	0.05	1.65	-6.40	< 0.001
LT (z)	$\mu_{z_{AI}} \geq \mu_{z_{BI}}$	9.63	0.05	1.65	-6.87	< 0.001
RT (x)	$\mu_{x_{AI}} \leq \mu_{x_{BI}}$	3.72	0.05	1.65	-6.40	> 0.999
RT (z)	$\mu_{z_{AI}} \leq \mu_{z_{BI}}$	9.63	0.05	1.65	-6.87	> 0.999

Since $|t_0| > t_{\alpha/2,n_A+n_B-2}$ for the two-tailed (2T) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence to conclude that the mean number and the mean score for interactions identified by students between Drawing A and Drawing B are different. Additionally, since $t_0 < -t_{\alpha,n_A+n_B-2}$ for the left-tailed (LT) test with a p-value < 0.001 and since $t_0 < t_{\alpha,n_A+n_B-2}$ for the right-tailed (RT) test with a p-value > 0.999 at a significance level α of 0.05, there is statistical evidence to conclude that the mean number and the mean score for interactions identified by students in Drawing B is greater than Drawing A.

4.2.2.2 Paired Comparison Test Results for Interactions

The purpose of the paired comparison test was to determine whether the mean of the paired differences between Drawing A and Drawing B for the number and the score for interactions identified by students were statistically significant, and whether the difference between the two drawings was greater or less than zero (i.e. whether the number and the score for interactions was greater for Drawing A or Drawing B). The results of the paired comparison tests for interactions are presented in Table 4-5.

Table 4-5: Paired Comparison Test Results for Interactions

Drawing	**I for [S] Difference**		**I for [L] Difference**		**I for [C] Difference**		**x of I Difference**			**z of I Difference**		
	$\bar{d}_{x_{IS}}$	$\tilde{d}_{x_{IS}}$	$\bar{d}_{x_{IL}}$	$\tilde{d}_{x_{IL}}$	$\bar{d}_{x_{IC}}$	$\tilde{d}_{x_{IC}}$	$\bar{d}_{x_{IT}}$	$\tilde{d}_{x_{IT}}$	$S_{d_{x_{IT}}}$	$\bar{d}_{z_{IT}}$	$\tilde{d}_{z_{IT}}$	$S_{d_{z_{IT}}}$
BA $n_{BA} = 97$	0.52	0	1.23	0	0.03	0	1.77	1	2.26	3.06	2	3.87

Test	H_0	S_d	α	$t_{critical}$	t_0	***p-value***
2T (x)	$\mu_{d_{x_I}} = 0$	2.26	0.05	1.98	7.74	< 0.001
2T (z)	$\mu_{d_{z_I}} = 0$	3.87	0.05	1.98	7.79	< 0.001
LT (x)	$\mu_{d_{x_I}} \geq 0$	2.26	0.05	1.66	7.74	> 0.999
LT (z)	$\mu_{d_{z_I}} \geq 0$	3.87	0.05	1.66	7.79	> 0.999
RT (x)	$\mu_{d_{x_I}} \leq 0$	2.26	0.05	1.66	7.74	< 0.001
RT (z)	$\mu_{d_{z_I}} \leq 0$	3.87	0.05	1.66	7.79	< 0.001

Since $|t_0| > t_{\alpha/2,n_{BA}-1}$ for the two-tailed (2T) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence to conclude that the mean of the paired differences between Drawing A and Drawing B for the number and the score for interactions identified by students are different. Additionally, since $t_0 > -t_{\alpha,n_{BA}-1}$ for the left-tailed (LT) test with a p-value > 0.999 and since $t_0 > t_{\alpha,n_{BA}-1}$ for the right-tailed (RT) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence to conclude that the mean of the paired differences for the number and the score for interactions identified by students is greater than zero (i.e. the number and the score for interactions in Drawing B is greater than Drawing A).

4.2.2.3 Wilcoxon Signed Ranks Test Results for Interactions

The purpose of the Wilcoxon signed ranks test was to determine (from a non-parametric statistics perspective) whether the median and the mean of the paired differences between Drawing A and Drawing B for the number and the score for interactions identified by students were statistically significant, and whether the difference between the two drawings was greater or less than zero (i.e. whether the number and the score for interactions was greater for Drawing A or Drawing B). The results of the Wilcoxon signed ranks tests for interactions are presented in Table 4-6.

Table 4-6: Wilcoxon Signed Ranks Test Results for Interactions

Test	H_0	n_{BA}'	$\sum_{j=1}^{n_{BA}'} R_j$	$\sum_{j=1}^{n_{BA}'} R_j^2$	T	α	$z_{critical}$	p-value
2T (x)	$E(d_{x_I}) = 0$	57	1,653.00	62,559.50	6.61	0.05	1.96	< 0.001
2T (z)	$E(d_{z_I}) = 0$	60	1,822.00	73,436.00	6.72	0.05	1.96	< 0.001
LT (x)	$E(d_{x_I}) \geq 0$	57	1,653.00	62,559.50	6.61	0.05	1.64	> 0.999
LT (z)	$E(d_{z_I}) \geq 0$	60	1,822.00	73,436.00	6.72	0.05	1.64	> 0.999
RT (x)	$E(d_{x_I}) \leq 0$	57	1,653.00	62,559.50	6.61	0.05	1.64	< 0.001
RT (z)	$E(d_{z_I}) \leq 0$	60	1,822.00	73,436.00	6.72	0.05	1.64	< 0.001

Since $|T| > z_{1-\alpha/2}$ for the two-tailed (2T) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence (from a non-parametric statistics perspective) to conclude that the median and the mean of the paired differences between Drawing A and Drawing B for the number and the score for interactions identified by students are different. Additionally, since $T > -z_{1-\alpha}$ for the left-tailed (LT) test with a p-value > 0.999 and since $T > z_{1-\alpha}$ for the right-tailed (RT) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence (from a non-parametric statistics perspective) to conclude that the mean of the paired differences for the number and the score for interactions identified by students is greater than zero (i.e. the number and the score for interactions in Drawing B is greater than Drawing A).

4.2.3 Perspectives (Roles/Purposes) Results

In this section, the results of the interactions analysis are presented. The tabulated results for roles/purposes that were used to conduct the statistical tests are presented in Table 12-3 in Appendix F: Tabulated Results.

4.2.3.1 Two-Sample t-Test Results for Roles/Purposes

The purpose of the two-sample t-test was to determine whether there was a statistically significant difference between the mean number and the mean score for roles/purposes identified by students for Drawing A and Drawing B, and whether the mean number and the mean score for roles/purposes was greater for Drawing A or Drawing B. The results of the two-sample t-tests for roles/purposes are presented in Table 4-7.

Table 4-7: Two-Sample t-Test Results for Roles/Purposes

Drawing	**R for [S]**		**R for [L]**		**R for [C]**		**x of R**			**z of R**		
	$\bar{x}_{RS}$	$\tilde{x}_{RS}$	$\bar{x}_{RL}$	$\tilde{x}_{RL}$	$\bar{x}_{RC}$	$\tilde{x}_{RC}$	$\bar{x}_{RT}$	$\tilde{x}_{RT}$	$S_{x_{RT}}$	$\bar{z}_{RT}$	$\tilde{z}_{RT}$	$S_{z_{RT}}$
A $n_A = 97$	0.00	0	0.11	0	0.00	0	0.11	0	0.48	0.23	0	0.95
B $n_B = 97$	0.53	0	1.58	1	0.00	0	2.10	2	1.76	3.68	4	3.13

Test	H_0	S_p^2	α	$t_{critical}$	t_0	***p-value***
2T (x)	$\mu_{x_{AR}} = \mu_{x_{BR}}$	1.67	0.05	1.97	-10.72	< 0.001
2T (z)	$\mu_{z_{AR}} = \mu_{z_{BR}}$	5.34	0.05	1.97	-10.40	< 0.001
LT (x)	$\mu_{x_{AR}} \geq \mu_{x_{BR}}$	1.67	0.05	1.65	-10.72	< 0.001
LT (z)	$\mu_{z_{AR}} \geq \mu_{z_{BR}}$	5.34	0.05	1.65	-10.40	< 0.001
RT (x)	$\mu_{x_{AR}} \leq \mu_{x_{BR}}$	1.67	0.05	1.65	-10.72	> 0.999
RT (z)	$\mu_{z_{AR}} \leq \mu_{z_{BR}}$	5.34	0.05	1.65	-10.40	> 0.999

Since $|t_0| > t_{\alpha/2,n_A+n_B-2}$ for the two-tailed (2T) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence to conclude that the mean number and the mean score for roles/purposes identified by students between Drawing A and Drawing B are different. Additionally, since $t_0 < -t_{\alpha,n_A+n_B-2}$ for the left-tailed (LT) test with a p-value < 0.001 and since $t_0 < t_{\alpha,n_A+n_B-2}$ for the right-tailed (RT) test with a p-value > 0.999 at a significance level α of 0.05, there is statistical evidence to conclude that the mean number and the mean score for roles/purposes identified by students in Drawing B is greater than Drawing A.

4.2.3.2 Paired Comparison Test Results for Roles/Purposes

The purpose of the paired comparison test was to determine whether the mean of the paired differences between Drawing A and Drawing B for the number and the score for roles/purposes identified by students were statistically significant, and whether the difference between the two drawings was greater or less than zero (i.e. whether the number and the score for roles/purposes was greater for Drawing A or Drawing B). The results of the paired comparison tests for roles/purposes are presented in Table 4-8.

Table 4-8: Paired Comparison Test Results for Roles/Purposes

Drawing	R for [S] Difference		R for [L] Difference		R for [C] Difference		x of R Difference			z of R Difference		
	$\bar{d}_{x_{RS}}$	$\tilde{d}_{x_{RS}}$	$\bar{d}_{x_{RL}}$	$\tilde{d}_{x_{RL}}$	$\bar{d}_{x_{RC}}$	$\tilde{d}_{x_{RC}}$	$\bar{d}_{x_{RT}}$	$\tilde{d}_{x_{RT}}$	$S_{d_{x_{RT}}}$	$\bar{d}_{z_{RT}}$	$\tilde{d}_{z_{RT}}$	$S_{d_{z_{RT}}}$
BA $\boldsymbol{n_{BA} = 97}$	0.53	0	1.46	1	0.00	0	1.99	2	1.78	3.45	3	3.14

Test	H_0	S_d	α	$t_{critical}$	t_0	*p-value*
2T (x)	$\mu_{d_{x_R}} = 0$	1.78	0.05	1.98	10.99	< 0.001
2T (z)	$\mu_{d_{z_R}} = 0$	3.14	0.05	1.98	10.82	< 0.001
LT (x)	$\mu_{d_{x_R}} \geq 0$	1.78	0.05	1.66	10.99	> 0.999
LT (z)	$\mu_{d_{z_R}} \geq 0$	3.14	0.05	1.66	10.82	> 0.999
RT (x)	$\mu_{d_{x_R}} \leq 0$	1.78	0.05	1.66	10.99	< 0.001
RT (z)	$\mu_{d_{z_R}} \leq 0$	3.14	0.05	1.66	10.82	< 0.001

Since $|t_0| > t_{\alpha/2,n_{BA}-1}$ for the two-tailed (2T) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence to conclude that the mean of the paired differences between Drawing A and Drawing B for the number and the score for roles/purposes identified by students are different. Additionally, since $t_0 > -t_{\alpha,n_{BA}-1}$ for the left-tailed (LT) test with a p-value > 0.999 and since $t_0 > t_{\alpha,n_{BA}-1}$ for the right-tailed (RT) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence to conclude that the mean of the paired differences for the number and the score for roles/purposes identified by students is greater than zero (i.e. the number and the score for roles/purposes in Drawing B is greater than Drawing A).

4.2.3.3 Wilcoxon Signed Ranks Test Results for Roles/Purposes

The purpose of the Wilcoxon signed ranks test was to determine (from a non-parametric statistics perspective) whether the median and the mean of the paired differences between

Drawing A and Drawing B for the number and the score for roles/purposes identified by students were statistically significant, and whether the difference between the two drawings was greater or less than zero (i.e. whether the number and the score for roles/purposes was greater for Drawing A or Drawing B). The results of the Wilcoxon signed ranks tests for roles/purposes are presented in Table 4-9.

Table 4-9: Wilcoxon Signed Ranks Test Results for Roles/Purposes

Test	H_0	n_{BA}'	$\sum_{j=1}^{n_{BA}'} R_j$	$\sum_{j=1}^{n_{BA}'} R_j^2$	T	α	$z_{critical}$	p-value
2T (x)	$E(d_{x_R}) = 0$	74	2,717.00	135,958.50	7.37	0.05	1.96	< 0.001
2T (z)	$E(d_{z_R}) = 0$	74	2,706.00	136,635.50	7.32	0.05	1.96	< 0.001
LT (x)	$E(d_{x_R}) \geq 0$	74	2,717.00	135,958.50	7.37	0.05	1.64	> 0.999
LT (z)	$E(d_{z_R}) \geq 0$	74	2,706.00	136,635.50	7.32	0.05	1.64	> 0.999
RT (x)	$E(d_{x_R}) \leq 0$	74	2,717.00	135,958.50	7.37	0.05	1.64	< 0.001
RT (z)	$E(d_{z_R}) \leq 0$	74	2,706.00	136,635.50	7.32	0.05	1.64	< 0.001

Since $|T| > z_{1-\alpha/2}$ for the two-tailed (2T) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence (from a non-parametric statistics perspective) to conclude that the median and the mean of the paired differences between Drawing A and Drawing B for the number and the score for roles/purposes identified by students are different. Additionally, since $T > -z_{1-\alpha}$ for the left-tailed (LT) test with a p-value > 0.999 and since $T > z_{1-\alpha}$ for the right-tailed (RT) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence (from a non-parametric statistics perspective) to conclude that the mean of the paired differences for the number and the score for roles/purposes identified by students is greater than zero (i.e. the number and the score for roles/purposes in Drawing B is greater than Drawing A).

4.2.4 Totals Results

In this section, the results of the totals analysis are presented. The tabulated results for totals that were used to conduct the statistical tests are presented in Table 12-4 in Appendix F: Tabulated Results.

4.2.4.1 Two-Sample t-Test Results for Totals

The purpose of the two-sample t-test was to determine whether there was a statistically significant difference between the mean number and the mean score for total elements, interactions, and roles/purposes identified by students for Drawing A and Drawing B, and whether the mean number and the mean score for total elements, interactions, and roles/purposes was greater for Drawing A or Drawing B. The results of the two-sample t-tests for totals are presented in Table 4-10.

Table 4-10: Two-Sample t-Test Results for Totals

Drawing	**T for [S]**		**T for [L]**		**T for [C]**		**x of Totals**			**z of Totals**		
	$\bar{x}_{ST}$	$\tilde{x}_{ST}$	$\bar{x}_{LT}$	$\tilde{x}_{LT}$	$\bar{x}_{CT}$	$\tilde{x}_{CT}$	$\bar{x}_T$	$\tilde{x}_T$	S_{x_T}	$\bar{z}_T$	$\tilde{z}_T$	S_{z_T}
A $n_A = 97$	2.62	3	3.15	3	0.22	0	5.99	5	2.97	9.58	8	5.83
B $n_B = 97$	4.10	3	7.61	7	0.69	0	12.40	12	4.77	21.39	19	8.99

Test	H_0	S_p^2	α	$t_{critical}$	t_0	***p-value***
2T (x)	$\mu_{x_{AT}} = \mu_{x_{BT}}$	15.79	0.05	1.97	-11.24	< 0.001
2T (z)	$\mu_{z_{AT}} = \mu_{z_{BT}}$	57.44	0.05	1.97	-10.86	< 0.001
LT (x)	$\mu_{x_{AT}} \geq \mu_{x_{BT}}$	15.79	0.05	1.65	-11.24	< 0.001
LT (z)	$\mu_{z_{AT}} \geq \mu_{z_{BT}}$	57.44	0.05	1.65	-10.86	< 0.001
RT (x)	$\mu_{x_{AT}} \leq \mu_{x_{BT}}$	15.79	0.05	1.65	-11.24	> 0.999
RT (z)	$\mu_{z_{AT}} \leq \mu_{z_{BT}}$	57.44	0.05	1.65	-10.86	> 0.999

Since $|t_0| > t_{\alpha/2,n_A+n_B-2}$ for the two-tailed (2T) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence to conclude that the mean number and the mean score for total elements, interactions, and roles/purposes identified by students between Drawing A and Drawing B are different. Additionally, since $t_0 < -t_{\alpha,n_A+n_B-2}$ for the left-tailed (LT) test with a p-value < 0.001 and since $t_0 < t_{\alpha,n_A+n_B-2}$ for the right-tailed (RT) test with a p-value > 0.999 at a significance level α of 0.05, there is statistical evidence to conclude that the mean number and the mean score for total elements, interactions, and roles/purposes identified by students in Drawing B is greater than Drawing A.

4.2.4.2 Paired Comparison Test Results for Totals

The purpose of the paired comparison test was to determine whether the mean of the paired differences between Drawing A and Drawing B for the number and the score for total elements, interactions, and roles/purposes identified by students were statistically significant, and whether the difference between the two drawings was greater or less than zero (i.e. whether the number and the score for total elements, interactions, and roles/purposes was greater for Drawing A or Drawing B). The results of the paired comparison tests for totals are presented in Table 4-11.

Table 4-11: Paired Comparison Test Results for Totals

Drawing	**Totals [S] Difference**		**Totals [L] Difference**		**Totals [C] Difference**		**x Totals Difference**			**z Totals Difference**		
	$\bar{d}_{x_{ST}}$	$\tilde{d}_{x_{ST}}$	$\bar{d}_{x_{LT}}$	$\tilde{d}_{x_{LT}}$	$\bar{d}_{x_{CT}}$	$\tilde{d}_{x_{CT}}$	$\bar{d}_{x_T}$	$\tilde{d}_{x_T}$	$S_{d_{x_T}}$	$\bar{d}_{z_T}$	$\tilde{d}_{z_T}$	$S_{d_{z_T}}$
BA $n_{BA} = 97$	1.48	1	4.45	4	0.47	0	6.41	6	3.89	11.81	10	7.22

Test	H_0	S_d	α	$t_{critical}$	t_0	***p-value***
2T (x)	$\mu_{d_{x_T}} = 0$	3.89	0.05	1.98	16.22	< 0.001
2T (z)	$\mu_{d_{z_T}} = 0$	7.22	0.05	1.98	16.12	< 0.001
LT (x)	$\mu_{d_{x_T}} \geq 0$	3.89	0.05	1.66	16.22	> 0.999
LT (z)	$\mu_{d_{z_T}} \geq 0$	7.22	0.05	1.66	16.12	> 0.999
RT (x)	$\mu_{d_{x_T}} \leq 0$	3.89	0.05	1.66	16.22	< 0.001
RT (z)	$\mu_{d_{z_T}} \leq 0$	7.22	0.05	1.66	16.12	< 0.001

Since $|t_0| > t_{\alpha/2, n_{BA}-1}$ for the two-tailed (2T) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence to conclude that the mean of the paired differences between Drawing A and Drawing B for the number and the score for total elements, interactions, and roles/purposes identified by students are different. Additionally, since $t_0 > -t_{\alpha, n_{BA}-1}$ for the left-tailed (LT) test with a p-value > 0.999 and since $t_0 >$

$t_{\alpha,n_{BA}-1}$ for the right-tailed (RT) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence to conclude that the mean of the paired differences for the number and the score for total elements, interactions, and roles/purposes identified by students is greater than zero (i.e. the number and the score for total elements, interactions, and roles/purposes in Drawing B is greater than Drawing A).

4.2.4.3 Wilcoxon Signed Ranks Test Results for Totals

The purpose of the Wilcoxon signed ranks test was to determine (from a non-parametric statistics perspective) whether the median and the mean of the paired differences between Drawing A and Drawing B for the number and the score for total elements, interactions, and roles/purposes identified by students were statistically significant, and whether the difference between the two drawings was greater or less than zero (i.e. whether the number and the score for total elements, interactions, and roles/purposes was greater for Drawing A or Drawing B). The results of the Wilcoxon signed ranks tests for totals are presented in Table 4-12.

Table 4-12: Wilcoxon Signed Ranks Test Results for Totals

Test	H_0	n_{BA}'	$\sum_{j=1}^{n_{BA}'} R_j$	$\sum_{j=1}^{n_{BA}'} R_j^2$	T	α	$z_{critical}$	p-value
2T (x)	$E(d_{x_T}) = 0$	94	4,458.00	280,624.00	8.42	0.05	1.96	< 0.001
2T (z)	$E(d_{z_T}) = 0$	95	4,556.00	290,028.00	8.46	0.05	1.96	< 0.001
LT (x)	$E(d_{x_T}) \geq 0$	94	4,458.00	280,624.00	8.42	0.05	1.64	> 0.999
LT (z)	$E(d_{z_T}) \geq 0$	95	4,556.00	290,028.00	8.46	0.05	1.64	> 0.999
RT (x)	$E(d_{x_T}) \leq 0$	94	4,458.00	280,624.00	8.42	0.05	1.64	< 0.001
RT (z)	$E(d_{z_T}) \leq 0$	95	4,556.00	290,028.00	8.46	0.05	1.64	< 0.001

Since $|T| > z_{1-\alpha/2}$ for the two-tailed (2T) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence (from a non-parametric statistics perspective) to conclude that the median and the mean of the paired differences between Drawing A and Drawing B for the number and the score for total elements, interactions, and roles/purposes identified by students are different. Additionally, since $T > -z_{1-\alpha}$ for the left-tailed (LT) test with a p-value > 0.999 and since $T > z_{1-\alpha}$ for the right-tailed (RT) test with a p-value < 0.001 at a significance level α of 0.05, there is statistical evidence (from a non-parametric statistics perspective) to conclude that the mean of the paired differences for the number and the score for total elements, interactions, and roles/purposes identified by students is greater than zero (i.e. the number and the score for total elements, interactions, and roles/purposes in Drawing B is greater than Drawing A).

4.3 Exploratory Results

In this section, exploratory results from the experiment are presented and discussed. These exploratory results include student familiarity with fish tanks, differences between middle and high school students, differences between groups, and differences between instructors.

4.3.1 Student Familiarity Rating for Fish Tanks

During the experiment in this research, students were asked to provide a rating on a scale of one (1) to five (5) to indicate their level of familiarity with fish tanks. A rating of one (1) represented “not at all familiar” and a rating of five (5) represented “extremely familiar”. The average and median ratings for the ninety-seven (97) students in the experiment were 2.85 and 3.00 respectively, which corresponded to a rating of “somewhat familiar”. The purpose of collecting this information from students was to determine whether student familiarity with fish tanks could be used to explain, or to predict, the total score students received on their fish-tank system drawings. A test to check for this relationship was performed by plotting each student’s familiarity rating versus their total score for Drawing B and determining the coefficient of determination (R^2), which measures the proportion in variability of score explained by the familiarity rating (Montgomery, 2013b). Based on the plot shown in Figure 4-1, there is no evidence to conclude that the familiarity rating students provided can be used as a predictor of total score in Drawing B since the R^2 value is 0.01 (1.00%).

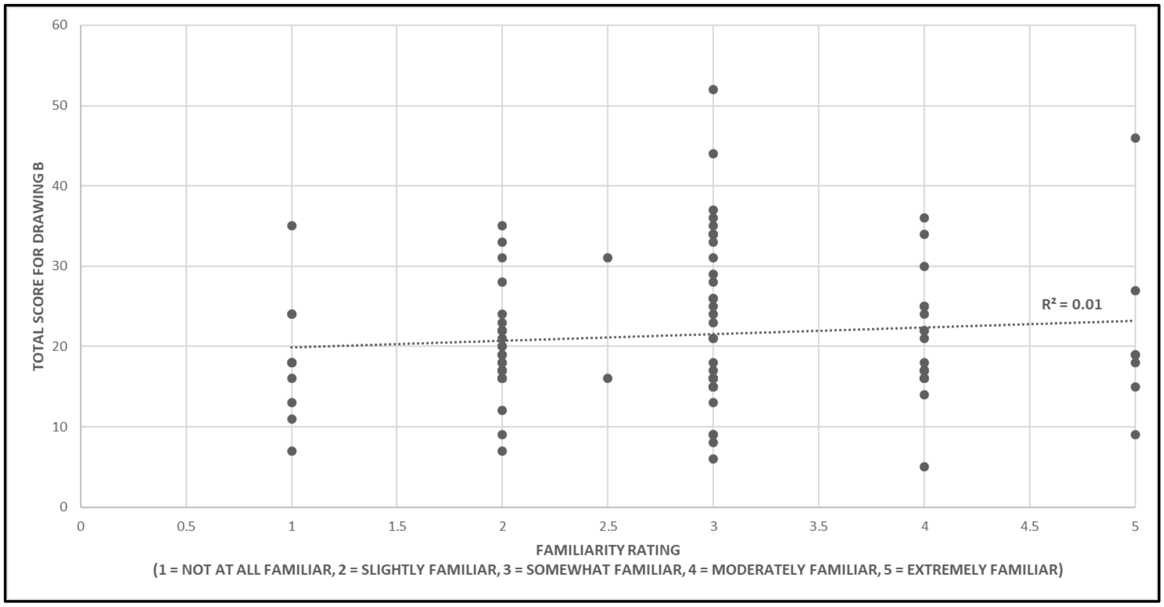

Figure 4-1: Student Fish Tank Familiarity Rating vs. Total Score for Drawing B

4.3.2 Differences between Middle School and High School Students

The experiment in this research was conducted with forty-two (42) middle school (MS) students and fifty-five (55) high school (HS) students from the Science and Math Investigative Learning Experiences (SMILE) Program ($n_{iMS} = 42$ MS students and $n_{iHS} = 55$ HS students for each *i* drawing [A, B, BA]). Although the experiment was conducted consistently for both types of students, an analysis was conducted to determine whether there were differences between MS and HS students with respect to systems thinking learning. This analysis consisted of two parts. For both parts, two statistical tests were performed – one test for number (*x*) and one test for score (*z*) – using the two-sample t-test (see section 3.2.5.1 for details about this test). In part one (section 4.3.2.1), the differences between MS and HS students for Drawing B only were analyzed. In part two (section 4.3.2.2), the differences between MS and HS students from Drawing A to Drawing B (i.e. the differences in systems thinking learning) were analyzed. The tabulated results used to conduct this analysis for MS and HS students are presented in Table 12-5 and Table 12-6 respectively in Appendix F: Tabulated Results.

4.3.2.1 MS and HS Student Analysis for Drawing B

In the first part of this analysis, the differences between MS and HS students with respect to the mean number (*x*) and mean score (*z*) for total elements, interactions, and roles/purposes identified were analyzed for Drawing B only. The two-tailed null (H_0) and alternative (H_1) hypotheses for the two-sample t-test for mean number (*x*) were: $H_0: \mu_{x_{BTMS}} = \mu_{x_{BTHS}}$ and $H_1: \mu_{x_{BTMS}} \neq \mu_{x_{BTHS}}$. The two-tailed null and alternative hypotheses for the two-sample t-test for mean score (*z*) were: $H_0: \mu_{z_{BTMS}} = \mu_{z_{BTHS}}$ and $H_1: \mu_{z_{BTMS}} \neq \mu_{z_{BTHS}}$. Conducting the two-tailed test allowed for conclusions to be drawn about whether the mean number and the mean score for total elements, interactions, and roles/purposes identified by HS students for Drawing B only were different than MS students. If H_0 was rejected (i.e. if $|t_0| > t_{\alpha/2, n_{BMS}+n_{BHS}-2}$), there was evidence to show that the means for MS and HS students were different meaning that one-sided hypothesis tests needed to be conducted to determine whether the mean was greater for MS or HS students.

The null and alternative hypotheses for the one-sided two-sample t-test (left-tailed) to determine whether the mean number (*x*) for HS students was greater than MS students were stated as: $H_0: \mu_{x_{BTMS}} \geq \mu_{x_{BTHS}}$ and $H_1: \mu_{x_{BTMS}} < \mu_{x_{BTHS}}$. The null and alternative hypotheses for the one-sided two-sample t-test (left-tailed) to determine whether the mean score (*z*) for HS students was greater than MS students were stated as: $H_0: \mu_{z_{BTMS}} \geq \mu_{z_{BTHS}}$ and $H_1: \mu_{z_{BTMS}} < \mu_{z_{BTHS}}$. If H_0 was rejected (i.e. if $t_0 < -t_{\alpha, n_{BMS}+n_{BHS}-2}$), there was evidence to show that the means for HS students were greater than MS students. Alternatively, the null and alternative hypotheses for the one-sided two-sample t-test (right-tailed) to determine whether the mean number (*x*) for MS students was greater than HS students were stated as: $H_0: \mu_{x_{BTMS}} \leq \mu_{x_{BTHS}}$ and $H_1: \mu_{x_{BTMS}} > \mu_{x_{BTHS}}$. The null and alternative hypotheses for the one-sided two-sample t-test (right-tailed) to determine whether the mean score (*z*) for MS students was greater than HS students were stated as: $H_0: \mu_{z_{BTMS}} \leq \mu_{z_{BTHS}}$ and $H_1: \mu_{z_{BTMS}} > \mu_{z_{BTHS}}$. If H_0 was rejected (i.e. if $t_0 >$

$t_{\alpha,n_{BMS}+n_{BHS}-2}$), there was evidence to show that the means for MS students were greater than HS students.

Since $|t_0| > t_{\alpha/2,n_{BMS}+n_{BHS}-2}$ for both mean number (*x*) and mean score (*z*) with a p-value ≤ 0.05 at a significance level α of 0.05, there was statistical evidence to conclude that the mean number and the mean score for total elements, interactions, and roles/purposes identified by HS students and MS students for Drawing B are different. However, the p-values are close to the significance level (0.03 and 0.05 for number (*x*) and score (*z*) respectively) which means the magnitude of difference between MS and HS students is not high. Additionally, since $t_0 < -t_{\alpha,n_{BMS}+n_{BHS}-2}$ with a p-value $\approx$ 0.02 and since $t_0 < t_{\alpha,n_{BMS}+n_{BHS}-2}$ with a p-value $\approx$ 0.98 at a significance level α of 0.05, there is statistical evidence to conclude that the mean number and the mean score for elements, interactions, and roles/purposes identified by HS students is greater than MS students for Drawing B.

A comparison of the sample statistics shows that HS students identified an average of two to three (2-3) more elements, interactions, and roles/purposes and scored an average of three to four (3-4) points higher than MS students in Drawing B. Additionally, HS students identified more individual elements, interactions, and roles/purposes and scored higher across all three systems thinking learning levels for Drawing B compared to MS students. The most significant difference between HS and MS students for Drawing B was at the literacy level where HS students identified an average of one to two (1-2) more elements, interactions, and roles/purposes than MS students. These results provided evidence that HS students were likely able to recall more information or knowledge about the elements, interactions, and roles/purposes in a fish-tank system than MS students, but these results did not provide evidence that HS students were likely to be better systems thinkers than MS students. In part two of this analysis, the question of whether HS students improved, or learned, more than MS students with respect to systems thinking during the experiment was analyzed.

4.3.2.2 MS and HS Student Analysis for Systems Thinking Learning

In the second part of this analysis, the differences between MS and HS students with respect to the mean differences in number (*x*) and in score (*z*) for total elements, interactions, and roles/purposes identified were analyzed between Drawing A and Drawing B [Drawing BA = Drawing B - Drawing A]. The two-tailed null (H_0) and alternative (H_1) hypotheses for the two-sample t-test for mean differences in number (*x*) were stated as: $H_0\colon \mu_{x_{BATMS}} = \mu_{x_{BATHS}}$ and $H_1\colon \mu_{x_{BATMS}} \neq \mu_{x_{BATHS}}$. The two-tailed null and alternative hypotheses for the two-sample t-test for mean differences in score (*z*) were stated as: $H_0\colon \mu_{z_{BATMS}} = \mu_{z_{BATHS}}$ and $H_1\colon \mu_{z_{BATMS}} \neq \mu_{z_{BATHS}}$. Conducting the two-tailed test allowed for conclusions to be drawn about whether the mean differences in number and in score for total elements, interactions, and roles/purposes identified by HS students between Drawing A and Drawing B were different than MS students. If H_0 was rejected (i.e. if $|t_0| > t_{\alpha/2, n_{BAMS}+n_{BAHS}-2}$), there was evidence to show that the mean differences for MS and HS students were different meaning that one-sided hypothesis tests needed to be conducted to determine whether the mean differences were greater for MS or HS students.

The null and alternative hypotheses for the one-sided two-sample t-test (left-tailed) to determine whether the mean differences in number (*x*) for HS students was greater than MS students were stated as: $H_0\colon \mu_{x_{BATMS}} \geq \mu_{x_{BATHS}}$ and $H_1\colon \mu_{x_{BATMS}} < \mu_{x_{BATHS}}$. The null and alternative hypotheses for the one-sided two-sample t-test (left-tailed) to determine whether the mean differences in score (*z*) for HS students was greater than MS students were stated as: $H_0\colon \mu_{z_{BATMS}} \geq \mu_{z_{BATHS}}$ and $H_1\colon \mu_{z_{BATMS}} < \mu_{z_{BATHS}}$. If H_0 was rejected (i.e. if $t_0 < -t_{\alpha, n_{BAMS}+n_{BAHS}-2}$), there was evidence to show that the mean differences for HS students were greater than MS students. Alternatively, the null and alternative hypotheses for the one-sided two-sample t-test (right-tailed) to determine whether the mean differences in number (*x*) for MS students was greater than HS students were stated as: $H_0\colon \mu_{x_{BATMS}} \leq \mu_{x_{BATHS}}$ and $H_1\colon \mu_{x_{BATMS}} > \mu_{x_{BATHS}}$. The null and alternative hypotheses for the one-sided two-sample t-test (right-tailed) to determine whether the mean differences in score (*z*) for MS students was greater than HS students were stated as: $H_0\colon \mu_{z_{BATMS}} \leq \mu_{z_{BATHS}}$ and

$H_1: \mu_{z_{BATMS}} > \mu_{z_{BATHS}}$. If H_0 was rejected (i.e. if $t_0 > t_{\alpha, n_{BAMS}+n_{BAHS}-2}$), there was evidence to show that the mean differences for MS students were greater than HS students.

Since $|t_0| < t_{\alpha/2, n_{BAMS}+n_{BAHS}-2}$ for both the mean differences in number (x) and score (z) with a p-value ≥ 0.34 at a significance level α of 0.05, there was statistical evidence to conclude that the mean differences in number and the mean differences in score for total elements, interactions, and roles/purposes identified by HS students and MS students between Drawing A and Drawing B are not different. A comparison of the sample statistics shows that both HS and MS students identified an average of five to six (5-6) more elements, interactions, and roles/purposes and scored an average of ten to twelve (10-12) points higher in Drawing B compared to Drawing A. Additionally, the most significant improvement for both MS and HS students was at the literacy level of systems thinking where both types of students identified an average of four (4) more elements, interactions, and roles/purposes between Drawing B and A. These results provided evidence to show that the improvement in systems thinking learning for both HS students and MS students was not statistically different between Drawing A and Drawing B. Although HS students were able to recall more information or knowledge than MS students about a fish-tank system, HS students did not improve more in systems thinking learning than MS students. These results might be due to HS students being older and having more experience than MS students, but age and experience did not necessarily mean that HS students were better systems thinkers than MS students. This means that the method to measure systems thinking learning in the context of a fish-tank system was acceptable for both MS and HS students.

4.3.3 Differences between Groups and Instructors

The experiment in this research was conducted with nine (9) total groups – five (5) groups of high-school (HS) students and four (4) groups of middle-school (MS) students. The experiment was also conducted by three (3) different instructor combinations: 1) Instructor #1 + Instructor #2, 2) Instructor #1, and 3) Instructor #2. In this section, the differences between both groups (section 4.3.3.1) and instructors (section 4.3.3.2) were analyzed to determine if either factor had a significant effect on the results presented in section 4.2. To analyze the differences between groups and instructors, an analysis of variance (ANOVA) was conducted to draw inferences about whether there were statistically significant differences between groups and/or instructors and also the sources of any differences (i.e. the source of any variabilities).

The ANOVA procedure described in this section was the same for both groups and instructors. The ANOVA was conducted as a single factor experiment with a number of levels, or treatments. The factor of interest was the groups in the first analysis (with a = 9 groups) and instructors in the second analysis (with a = 3 instructors). A random effects ANOVA model was chosen for the groups analysis as there were a large number of groups to choose from within the population of factor levels, but only a = 9 random levels were included in the experiment (Montgomery, 2013b). Since the experimental groups were chosen randomly, this type of analysis allowed inferences to be drawn about the entire population of groups instead of only for the groups considered. Alternatively, a fixed effects ANOVA model was chosen for the analysis of instructors as only the three instructor combinations were available for the experiment and the inferences from this analysis only needed to be drawn about the instructors in the experiment and not the entire instructor population (Montgomery, 2013b).

The procedure for both the random effects and the fixed effects ANOVA model were identical, except for how the random effects model was used to draw conclusions about the two sources of variation related to the entire population of groups for a single factor experiment. The first source of variation was between the groups, denoted as σ_{τ}^{2}, and the second source of variation was within the groups, denoted as σ^{2}. This meant the variance (V) of any observation was equal to the sum of both sources of variances as shown in Equation 4-1, where d_{wv} was the paired difference for the wv^{th} student in the experiment (w = group and v = student number in the group). Similar to the paired comparison and Wilcoxon tests, the paired difference was computed as $d_j = y_{Bj} - y_{Aj}$, where y_{ij} was defined as a sample from a systems thinking learning concept of interest for each i drawing

[A, B, BA] and *j* student (see Equation 3-3 in section 3.2.5.2). In the ANOVA model, however, only the paired difference in the total scores between Drawing B and Drawing A were considered for each student such that $d_{z_{jT}} = z_{BjT} - z_{AjT}$ (readers should refer to Table 9-1 in Appendix C: Glossary of Variables for variable definitions). The paired difference in total score $d_{z_{jT}}$ for each student *j* was then matched with its respective group to create each $d_{z_{wv}}$ value.

Equation 4-1: Variance of Any Paired Sample in ANOVA Random Effects Model

$$V\left(d_{z_{wv}}\right) = \sigma_\tau^2 + \sigma^2$$

The calculation of the sum of squares identity that separates the total variability of the observations into two components, shown in Equation 4-2, was the same for both the random effects and fixed effects ANOVA analysis (Montgomery, 2013b). The two variance components are the sum of squares for the treatments ($SS_{Treatments}$), which measured the variability between groups or instructors, and the sum of squares for error (SS_{Error}), which measured the variability within groups or instructors.

Equation 4-2: Sum of Squares Identity in a Single Factor ANOVA

$$SS_{Total} = SS_{Treatments} + SS_{Error}$$

Since the number of observations within each group and for each instructor was different, an unbalanced single factor ANOVA design had to be used (Montgomery, 2013b). Therefore, n_w was used to denote the number of observations for each group or instructor w (w = 1, 2 … a) where a equaled the total number of groups or instructors. Additionally, the total number of observations $= N = \sum_{w=1}^{a} n_w$. The SS_{Total}, $SS_{Treatments}$, and SS_{Error} in the unbalanced design were calculated according to Equation 4-3, Equation 4-4, and Equation 4-5 respectively (with v = student number in group w for the groups analysis and v = group number for instructor w for the instructors analysis).

Equation 4-3: Sum of Squares for Total (Unbalanced Design)

$$SS_{Total} = \sum_{w=1}^{a} \sum_{v=1}^{n_w} d_{z_{wv}}^2 - \frac{{d_{z..}}^2}{N}$$

Equation 4-4: Sum of Squares for Treatments (Unbalanced Design)

$$SS_{Treatments} = \sum_{w=1}^{a} \frac{{d_{z_{w\cdot}}}^2}{n_w} - \frac{{d_{z..}}^2}{N}$$

Equation 4-5: Sum of Squares for Error (Unbalanced Design)

$$SS_{Error} = SS_{Total} - SS_{Treatments}$$

In order to calculate the test statistic F_0, the mean squares for both the treatments and the error needed to be calculated by dividing each sum of squares value by its respective degrees of freedom. For $SS_{Treatments}$ this meant dividing by $a - 1$ degrees of freedom and for SS_{Error} this meant dividing by $N - a$ degrees of freedom. Now the test statistic F_0 could be calculated according to Equation 4-6. The hypothesis test for the fixed effects model was stated in terms of the individual treatment means as: $H_0: \mu_1 = \mu_2 = \cdots \mu_a = 0$ and H_1: one or more μ_w is different. The hypothesis test for the random effects model differed from the fixed effects model in that the variance of interest was σ_τ^2 (i.e. the variation between groups) instead of the individual treatment effects (Montgomery, 2013b). Therefore, the hypothesis test for the random effects model was stated as: $H_0: \sigma_\tau^2 = 0$ and $H_1: \sigma_\tau^2 > 0$. In both models, H_0 was rejected for a specific significance level α if $F_0 > F_{\alpha,a-1,N-a}$ (Montgomery, 2013b). If H_0 was rejected, this meant that there were statistically significant differences between the treatments (i.e. the groups and/or the instructors).

Equation 4-6: Test Statistic for Single Factor ANOVA

$$F_0 = \frac{\frac{SS_{Treatments}}{a-1}}{\frac{SS_{Error}}{N-a}} = \frac{MS_{Treatments}}{MS_{Error}}$$

The procedure for the fixed effects ANOVA model was complete with the calculation and evaluation of the test statistic. However, the last step in the random effects ANOVA model was to estimate the variance components introduced earlier, σ_τ^2 and σ^2. The estimates were calculated by first equating the observed and expected mean squares for each component which resulted in $MS_{Treatments} = \sigma^2 + n_0 * \sigma_\tau^2$ and $MS_{Error} = \sigma^2$, where n_0 was calculated according to Equation 4-7. Then, estimators of each variance component, $\hat{\sigma}_\tau^2$ and $\hat{\sigma}^2$, were determined according to Equation 4-8 and Equation 4-9 respectively. If $\hat{\sigma}_\tau^2 > \hat{\sigma}^2$ this meant that the variation between treatments, or groups, was greater than the variation within treatments, or groups.

Equation 4-7: Unequal Sample Size for Variance Component Estimator

$$n_0 = \frac{1}{a-1}\left[\sum_{w=1}^{a} n_w - \frac{\sum_{w=1}^{a} n_w^2}{\sum_{w=1}^{a} n_w}\right]$$

Equation 4-8: Estimator of Variance between Treatments (Groups)

$$\hat{\sigma}_\tau^2 = \frac{MS_{Treatments} - MS_{Error}}{n_0}$$

Equation 4-9: Estimator of Variance within Treatment (Groups)

$$\hat{\sigma}^2 = MS_{Error}$$

4.3.3.1 Differences between Groups in the Experiment

In this section the results from the ANOVA test for groups are presented. The purpose of the ANOVA test for groups was to determine whether there were statistically significant differences between the groups for elements, interactions, roles/purposes, and totals for the paired differences in score from Drawing A to Drawing B, and also to determine whether there was more variability between groups or within groups for the paired differences in score from Drawing A to Drawing B for elements, interactions, roles/purposes, and totals. The matrices of paired differences in score for elements, interactions, roles/purposes, and totals organized by group that were used to compute the results are presented in Table 13-1, Table 13-2, Table 13-3, and Table 13-4 respectively in Appendix G: ANOVA Matrices.

The results of the ANOVA for groups test for paired differences in element scores are presented in Table 4-13.

Table 4-13: ANOVA for Groups Test Results for Elements

<table>
<tr><th colspan="8">Fixed Effects ANOVA Model Results</th></tr>
<tr><th>Source of Variation</th><th>Sum of Squares</th><th>Degrees of Freedom</th><th>Mean Squares</th><th>F_o</th><th>α</th><th>$F_{\alpha,a-1,N-a}$</th><th>H_o</th></tr>
<tr><td>Groups</td><td>449.35</td><td>8</td><td>56.17</td><td>2.72</td><td>0.05</td><td>2.05</td><td rowspan="3">$\mu_1 = \cdots = \mu_a$</td></tr>
<tr><td>Error</td><td>1,814.98</td><td>88</td><td>20.62</td><td></td><td></td><td></td></tr>
<tr><td>Total</td><td>2,264.33</td><td>96</td><td></td><td></td><td></td><td></td></tr>
<tr><th colspan="8">Random Effects ANOVA Model Results</th></tr>
<tr><th>a (number of groups) & N (number of observations)</th><th>n_o</th><th colspan="2">$\hat{\sigma}^2$ (variance within groups, i.e. the students)</th><th colspan="2">$\hat{\sigma}_\tau^2$ (variance between groups)</th><th>$V(d_{wv})$ (total variance)</th><th>H_o</th></tr>
<tr><td>9 & 97</td><td>10.72</td><td colspan="2">20.62</td><td colspan="2">3.32</td><td>23.94</td><td>$\sigma_\tau^2 = 0$</td></tr>
</table>

Since $F_0 > F_{\alpha,a-1,N-a}$ with a p-value = 0.01 at a significance level α of 0.05, there was statistical evidence to conclude that there is a difference between groups for the paired differences in element scores. This means that some groups in the experiment scored higher for elements from Drawing A to Drawing B than other groups. Additionally, since $\hat{\sigma}_\tau^2 < \hat{\sigma}^2$ there was statistical evidence to conclude that most variability with respect to the paired differences in element scores for groups was attributable to differences within each group (i.e. the element scores for each student) rather than differences between groups. This means that differences between students with respect to the paired differences in element scores accounted for most of the variability in the experiment and other factors of variability between groups did not account for a significant amount of variability.

The results of the ANOVA for groups test for paired differences in interaction scores are presented in Table 4-14.

Table 4-14: ANOVA for Groups Test Results for Interactions

Fixed Effects ANOVA Model Results							
Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Squares**	F_o	α	$F_{\alpha,a-1,N-a}$	H_o
Groups	78.50	8	9.81	0.64	0.05	2.05	$\mu_1 = \cdots = \mu_a$
Error	1,359.13	88	15.44				
Total	1,437.63	96					
Random Effects ANOVA Model Results							
a (number of groups) & N (number of observations)	n_o	$\hat{\sigma}^2$ **(variance within groups, i.e. the students)**		$\hat{\sigma}_\tau^2$ **(variance between groups)**		$V(d_{wv})$ **(total variance)**	H_o
9 & 97	10.72	15.44		-0.53		14.92	$\sigma_\tau^2 = 0$

Since $F_0 < F_{\alpha,a-1,N-a}$ with a p-value = 0.75 at a significance level α of 0.05, there was statistical evidence to conclude that there is not a difference between groups for the paired differences in interaction scores. This means that all groups in the experiment scored statistically the same for interactions from Drawing A to Drawing B. Additionally, since $\hat{\sigma}_\tau^2 < \hat{\sigma}^2$ there was statistical evidence to conclude that most variability with respect to the paired differences in interaction scores for groups was attributable to differences within each group (i.e. the interaction scores for each student) rather than differences between groups. In the case of this test, $\hat{\sigma}_\tau^2$ was negative and can be assumed equal to zero (Montgomery, 2013b). This means that differences between students with respect to the paired differences in interaction scores accounted for most of the variability in the experiment and other factors of variability between groups did not account for a significant amount of variability.

The results of the ANOVA for groups test for paired differences in role/purpose scores are presented in Table 4-15.

Table 4-15: ANOVA for Groups Test Results for Roles/Purposes

Fixed Effects ANOVA Model Results							
Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Squares**	F_o	α	$F_{\alpha,a-1,N-a}$	H_o
Groups	104.98	8	13.12	1.37	0.05	2.05	$\mu_1 = \cdots = \mu_a$
Error	843.06	88	9.58				
Total	948.04	96					
Random Effects ANOVA Model Results							
a **(number of groups) &** N **(number of observations)**	n_o		$\hat{\sigma}^2$ **(variance within groups, i.e. the students)**	$\hat{\sigma}_\tau^2$ **(variance between groups)**		$V(d_{wv})$ **(total variance)**	H_o
9 & 97	10.72		9.58	0.33		9.91	$\sigma_\tau^2 = 0$

Since $F_0 < F_{\alpha,a-1,N-a}$ with a p-value = 0.22 at a significance level α of 0.05, there was statistical evidence to conclude that there is not a difference between groups for the paired differences in role/purpose scores. This means that all groups in the experiment scored statistically the same for roles/purposes from Drawing A to Drawing B. Additionally, since $\hat{\sigma}_\tau^2 < \hat{\sigma}^2$ there was statistical evidence to conclude that most variability with respect to the paired differences in role/purpose scores for groups was attributable to differences within each group (i.e. the role/purpose scores for each student) rather than differences between groups. This means that differences between students with respect to the paired differences in role/purpose scores accounted for most of the variability in the experiment and other factors of variability between groups did not account for a significant amount of variability.

The results of the ANOVA for groups test for paired differences in total scores are presented in Table 4-16.

Table 4-16: ANOVA for Groups Test Results for Totals

Fixed Effects ANOVA Model Results							
Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Squares**	F_o	α	$F_{\alpha,a-1,N-a}$	H_o
Groups	342.08	8	42.76	0.81	0.05	2.05	$\mu_1 = \cdots = \mu_a$
Error	4,658.58	88	52.94				
Total	5,000.66	96					
Random Effects ANOVA Model Results							
a (number of groups) & N (number of observations)	n_o	**$\hat{\sigma}^2$ (variance within groups, i.e. the students)**		**$\hat{\sigma}_\tau^2$ (variance between groups)**		**$V(d_{wv})$ (total variance)**	H_o
9 & 97	10.72	52.94		-0.95		51.99	$\sigma_\tau^2 = 0$

Since $F_0 < F_{\alpha,a-1,N-a}$ with a p-value = 0.60 at a significance level α of 0.05, there was statistical evidence to conclude that there is not a difference between groups for the paired differences in total scores. This means that all groups in the experiment scored statistically the same for totals from Drawing A to Drawing B. Additionally, since $\hat{\sigma}_\tau^2 < \hat{\sigma}^2$ there was statistical evidence to conclude that most variability with respect to the paired differences in total scores for groups was attributable to differences within each group (i.e. the total scores for each student) rather than differences between groups. In the case of this test, $\hat{\sigma}_\tau^2$ was negative and can be assumed equal to zero (Montgomery, 2013b). This means that differences between students with respect to the paired differences in total scores accounted for most of the variability in the experiment and other factors of variability between groups did not account for a significant amount of variability.

4.3.3.2 Differences between Instructors in the Experiment

In this section the results from the ANOVA test for instructors are presented. The purpose of the ANOVA test for instructors was to determine whether there were statistically significant differences between the instructors for the elements, interactions, roles/purposes, and totals identified by students reflected in the average paired differences in score for each group from Drawing A to Drawing B. The matrices for the average paired differences in score for elements, interactions, roles/purposes, and totals organized by instructor that were used to compute the results are presented in Table 13-5, Table 13-6, Table 13-7, and Table 13-8 respectively in Appendix G: ANOVA Matrices.

The results of the ANOVA for instructors test for average paired differences in element scores for each group are presented in Table 4-17.

Table 4-17: ANOVA for Instructors Test Results for Elements

Fixed Effects ANOVA Model Results							
Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Squares**	F_o	α	$F_{\alpha,a-1,N-a}$	H_o
Instructors	18.27	2	9.13	2.87	0.05	5.14	$\mu_1 = \cdots = \mu_a$
Error	19.09	6	3.18				
Total	37.36	8					

Since $F_0 < F_{\alpha,a-1,N-a}$ with a p-value = 0.13 at a significance level α of 0.05, there was statistical evidence to conclude that there was not a difference between instructors for the average paired differences in element scores for each group. This means that all groups in the experiment scored statistically the same for elements from Drawing A to Drawing B for all three instructors.

The results of the ANOVA for instructors test for average paired differences in interaction scores for each group are presented in Table 4-18.

Table 4-18: ANOVA for Instructors Test Results for Interactions

Fixed Effects ANOVA Model Results							
Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Squares**	F_o	α	$F_{\alpha,a-1,N-a}$	H_o
Instructors	2.34	2	1.17	1.50	0.05	5.14	$\mu_1 = \cdots = \mu_a$
Error	4.69	6	0.78				
Total	7.03	8					

Since $F_0 < F_{\alpha,a-1,N-a}$ with a p-value = 0.30 at a significance level α of 0.05, there was statistical evidence to conclude that there was not a difference between instructors for the average paired differences in interaction scores for each group. This means that all groups in the experiment scored statistically the same for interactions from Drawing A to Drawing B for all three instructors.

The results of the ANOVA for instructors test for average paired differences in role/purpose scores for each group are presented in Table 4-19.

Table 4-19: ANOVA for Instructors Test Results for Roles/Purposes

Fixed Effects ANOVA Model Results							
Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Squares**	F_o	α	$F_{\alpha,a-1,N-a}$	H_o
Instructors	1.15	2	0.58	0.35	0.05	5.14	$\mu_1 = \cdots = \mu_a$
Error	9.81	6	1.64				
Total	10.97	8					

Since $F_0 < F_{\alpha,a-1,N-a}$ with a p-value = 0.72 at a significance level α of 0.05, there was statistical evidence to conclude that there was not a difference between instructors for the average paired differences in role/purpose scores for each group. This means that all groups in the experiment scored statistically the same for roles/purposes from Drawing A to Drawing B for all three instructors.

The results of the ANOVA for instructors test for average paired differences in role/purpose scores for each group are presented in Table 4-20.

Table 4-20: ANOVA for Instructors Test Results for Totals

Fixed Effects ANOVA Model Results							
Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Squares**	F_o	α	$F_{\alpha,a-1,N-a}$	H_o
Instructors	7.63	2	3.82	1.10	0.05	5.14	$\mu_1 = \cdots = \mu_a$
Error	20.76	6	3.46				
Total	28.39	8					

Since $F_0 < F_{\alpha,a-1,N-a}$ with a p-value = 0.39 at a significance level α of 0.05, there was statistical evidence to conclude that there was not a difference between instructors for the average paired differences in total scores for each group. This means that all groups in the experiment scored statistically the same for totals from Drawing A to Drawing B for all three instructors.

4.3.4 Expected Learning and Systems Thinking Learning

One of the limitations for this research was that no control group could be included in the design of the experiment since the students who participated in the experiment were part of a pre-existing event and expected to learn about systems thinking. The lack of a control group limited the separation of the results into expected student learning attributable to the repeated task of drawing a fish-tank system and systems thinking learning attributable to teaching students about the systems thinking concepts. In this section a brief sensitivity analysis was conducted to examine the potential effects of expected learning upon the results presented in section 4.2.

For the purpose of this analysis, assume that from Drawing A to Drawing B students should have identified at least the same elements, interactions, and roles/purposes (i.e. Drawing A and Drawing B are identical). Therefore, a student who drew identical drawings for Drawing A and Drawing B would have zero learning attributable to expected learning and zero learning attributable to systems thinking learning. Furthermore, assume that from Drawing A to Drawing B students should have identified only as many elements, interactions, and roles/purposes to the point where their results became statistically significant (i.e. when the test statistic was equal to the critical value). Therefore, a student who performed the repeated task of drawing a fish-tank system without receiving any teaching about systems thinking would have had all learning attributable to expected learning and zero learning attributable to systems thinking learning. As the results are presented in section 4.2, all learning is attributed to systems thinking learning since no control group was used to measure the effect of expected learning. Therefore, this analysis examined the reduction required in the results for Drawing B for element, interaction, role/purpose, and total scores in order to reach the point between significance and non-significance for the one-tailed (left-tailed) two-sample t-test (which provided evidence to conclude that Drawing B was greater than Drawing A for elements, interactions, roles/purposes, and totals in section 4.2).

The point at which the element score became significant or non-significant is when the results of Drawing B were reduced by ~ 29.89%. Based on the assumptions made for this analysis, this means that the expected learning attributed for ~ 70% of student learning from Drawing A to Drawing B for the element score and that systems thinking learning attributed for ~ 30% of student learning from Drawing A to Drawing B for the element score. Therefore, this analysis indicated that overall student learning with respect to elements was more affected by the repeated task of drawing a fish-tank system (expected learning) than by learning to apply the systems thinking concept of distinctions as the skill of identifying elements.

The point at which the interaction score became significant or non-significant is when the results of Drawing B were reduced by ~ 81.35%. Based on the assumptions made for this analysis, this means that the expected learning attributed for ~ 19% of student learning from Drawing A to Drawing B for the interaction score and that systems thinking learning attributed for ~ 81% of student learning from Drawing A to Drawing B for the interaction score. Therefore, this analysis indicated that overall student learning with respect to interactions was less affected by the repeated task of drawing a fish-tank system (expected learning) than by learning to apply the systems thinking concept of relationships as the skill of identifying interactions.

The point at which the role/purpose score became significant or non-significant is when the results of Drawing B were reduced by ~ 89.23%. Based on the assumptions made for this analysis, this means that the expected learning attributed for approximately 11% of student learning from Drawing A to Drawing B for the role/purpose score and that systems thinking learning attributed for approximately 89% of student learning from Drawing A to

Drawing B for the role/purpose score. Therefore, this analysis indicated that overall student learning with respect to roles/purposes was less affected by the repeated task of drawing a fish-tank system (expected learning) than by learning to apply the systems thinking concept of perspectives as the skill of identifying roles/purposes.

The point at which the total score became significant or non-significant is when the results of Drawing B were reduced by ~ 49.45%. Based on the assumptions made for this analysis, this means that both the expected learning and the systems thinking learning attributed for ~ 50% of student learning from Drawing A to Drawing B for the total score. Therefore, this analysis indicated that overall student learning with respect to the totals was affected equally by the repeated task of drawing a fish-tank system (expected learning) and by learning to apply the systems thinking concepts as skills. The results of this analysis are summarized in Table 4-21.

Table 4-21: Results from Expected Learning and Systems Thinking Learning Analysis

Concept	**Expected Learning**	**Systems Thinking Learning**
Elements	~ 70%	~ 30%
Interactions	~ 19%	~ 81%
Roles/Purposes	~ 11%	~ 89%
Totals	~ 50%	~ 50%

Chapter 5

5 Conclusion

5.1 Features of this Research

The purpose of this research was to define and measure the initial systems thinking learning process for non-experts in the context of a fish-tank system to support future systems thinking curriculum development by and for non-experts. This purpose was achieved by fulfilling each of the following objectives:

- *To conceptualize the systems thinking curriculum development process by and for non-experts.*
    - The systems thinking curriculum development process was described and conceptualized in section 2.4 as the systems thinking curriculum development framework for non-experts (Figure 2-5).
    - This framework can help non-experts design systems thinking curriculum for other non-experts using the systematic processes of DMAIIC and Soft Systems Methodology coupled with the systemic approach of the System of Profound Knowledge.
- *To define the initial systems thinking learning process for non-experts.*
    - The systems thinking learning process was described and defined in section 2.5 as the systems thinking learning model (Figure 2-6).
    - This model defined the learning process in terms of three phases (Initial Learning, Rapid Learning, and Mastery Learning) which each consist of the three repeated systems thinking learning levels (sensibility, literacy, and capability). Systems thinking can be measured in each phase as a combined measurement of all three levels.
- *To design and conduct an experiment to measure the initial systems thinking learning process for non-experts.*

- An experiment was conducted with ninety-seven (97) middle and high school students in the SMILE Program to measure the effect of teaching students to apply the three systems thinking concepts of distinctions, relationships, and perspectives as skills.
- A methodology was developed to measure systems thinking learning in the context of a fish-tank system.
- Systems thinking learning was measured for two drawings of a fish-tank system in terms of elements (for the concept of distinctions), interactions (for the concept of relationships), and roles/purposes (for the concept of perspectives).
- The totals of elements, interactions, and roles/purposes were used to measure each student's improvement in systems thinking learning as a result of the experiment.

- *To contribute to the growth of systems literacy – the fostering of awareness and understanding of systems – in primary and secondary education (K-12).*
  - The experiment was used to teach K-12 students about the three systems thinking concepts of distinctions, relationships, and perspectives as skills to be applied in order to solve problems.
  - The results of the experiment show that the majority of students improved with respect to systems thinking learning as a result of being taught to apply each concept as a skill.

5.2 Findings from this Research

The results from this research support the four research questions and general hypotheses presented in sections 1.3 and 1.4 respectively, which are restated here in pairs for convenience.

(1) *First Question:* Is there a statistically significant difference between the elements identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of distinctions?

- *First Hypothesis:* There is a statistically significant difference between the elements identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of distinctions.

(2) *Second Question:* Is there a statistically significant difference between the interactions identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of relationships?

- *Second Hypothesis:* There is a statistically significant difference between the interactions identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of relationships.

(3) *Third Question:* Is there a statistically significant difference between the roles/purposes identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of perspectives?

- *Third Hypothesis:* There is a statistically significant difference between the roles/purposes identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of perspectives.

(4) *Fourth Question:* Is there a statistically significant difference between the totals of elements, interactions, and roles/purposes identified by non-experts in a fish-tank system drawing before and after learning about the three systems thinking concepts of distinctions, relationships, and perspectives?

- *Fourth Hypothesis:* There is a statistically significant difference between the totals of elements, interactions, and roles/purposes identified by non-experts in a fish-tank system drawing before and after learning about the three systems thinking concepts of distinctions, relationships, and perspectives.

5.2.1 Findings for Distinctions (Elements)

The first hypothesis is supported by the results of the elements analysis presented in section 4.2.1. The results of the statistical tests provide evidence to show that students identified an average of two to three (2-3) more elements in Drawing B compared to Drawing A, and that students scored an average of five (5) points higher in their element score in Drawing B compared to Drawing A. The most significant area of improvement for students with regards to elements was at the literacy level of systems thinking. Students identified an average of one to two (1-2) more elements at the literacy level in Drawing B compared to Drawing A.

In conclusion there is a statistically significant difference between the elements identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of distinctions. This conclusion means that teaching students to apply distinctions as a skill increased student learning of systems thinking with respect to distinctions, but primarily at the literacy level which only demonstrates knowledge about elements related to how the system works. Therefore, future learning opportunities should focus on student understanding of elements related to why the system works in a certain way (based on the problem situation) as a way to foster learning at the capability level.

5.2.2 Findings for Relationships (Interactions)

The second hypothesis is supported by the results of the interactions analysis presented in section 4.2.2. The results of the statistical tests provide evidence to show that students identified an average of one to two (1-2) more interactions in Drawing B compared to Drawing A, and that students scored an average of two to three (2-3) points higher in their interaction score in Drawing B compared to Drawing A. The most significant area of improvement for students with regards to interactions was at the literacy level of systems thinking. Students identified an average of one (1) more interaction at the literacy level in Drawing B compared to Drawing A.

In conclusion there is a statistically significant difference between the interactions identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of relationships. This conclusion means that teaching students to apply relationships as a skill increased student learning of systems thinking with respect to relationships, but primarily at the literacy level which only demonstrates knowledge about actions and reactions. Therefore, future learning opportunities should focus on student understanding of the cause-and-effect relationships between the actions and reactions as a way to foster learning at the capability level.

5.2.3 Findings for Perspectives (Roles/Purposes)

The third hypothesis is supported by the results of the roles/purposes analysis presented in section 4.2.3. The results of the statistical tests provide evidence to show that students identified an average of two (2) more roles/purposes in Drawing B compared to Drawing A, and that students scored an average of three (3) points higher in their role/purpose score in Drawing B compared to Drawing A. The most significant area of improvement for students with regards to roles/purposes was at the literacy level of systems thinking. Students identified an average of one (1) more roles/purposes at the literacy level in Drawing B compared to Drawing A.

In conclusion there is a statistically significant difference between the roles/purposes identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concept of perspectives. This conclusion means that teaching students to apply perspectives as a skill increased student learning of systems thinking with respect to perspectives, but primarily at the literacy level which only demonstrates knowledge about the role/purpose of elements as related to other elements. Therefore, future learning opportunities should focus on student understanding of why elements exist in a system using a systemic point-of-view as a way to foster learning at the capability level.

5.2.4 Findings for Totals

The fourth hypothesis is supported by the results of the totals analysis presented in section 4.2.4. The results of the statistical tests provide evidence to show that students identified an average of six (6) more total elements, interactions, and roles/purposes in Drawing B compared to Drawing A, and that students scored an average of ten to twelve (10-12) points higher in their total score in Drawing B compared to Drawing A. The most significant area of improvement for students with regards to the totals was at the literacy level of systems thinking. Students identified an average of four (4) more total elements, interactions, and roles/purposes at the literacy level in Drawing B compared to Drawing A.

In conclusion there is a statistically significant difference between the totals of elements, interactions, and roles/purposes identified by non-experts in a fish-tank system drawing before and after learning about the systems thinking concepts of distinctions, relationships, and perspectives. This conclusion means that teaching students to apply these concepts as skills increased student learning of systems thinking with respect to the concepts, but primarily at the literacy level which only demonstrates knowledge about systems thinking across these concepts. Therefore, future learning opportunities should focus on student understanding of systems thinking across these concepts as a way to foster learning at the capability level.

5.2.5 Systems Thinking Learning

To connect the results of the experiment with the systems thinking learning model presented in section 2.5, a method for visually representing each student's systems thinking learning for each drawing according to the model was developed. Figure 5-1 shows an example of this visual representation for student $j = 6$. The x-axis of the figure is time, which represents the three systems thinking learning levels (sensibility, literacy, and capability) for each drawing [A, B]. The y-axis of the figure is performance in terms of systems thinking learning which has been normalized as the percent of the total number of elements, interactions, and roles/purposes that a student identified. For example, suppose a student identified ten (10) total elements, interactions, and roles/purposes across all three levels for Drawing A. If three (3) of those items identified were at the sensibility level, then, the number of items for sensibility was divided by the total number of items to get a normalized percent of 30.00%. This process was repeated for the other two levels in order to plot points on the model connected by lines to represent the student's percent of the total number of elements, interactions, and roles/purposes they identified related to each learning level and drawing. A similar process was used to create the two bars shown for each learning level and drawing. However, these bars represent the average percent of the total number of elements, interactions, and roles/purposes identified by all students (the white bar on the left) and the median percent of the total number of elements, interactions, and roles/purposes identified by all students (the shaded bar on the right).

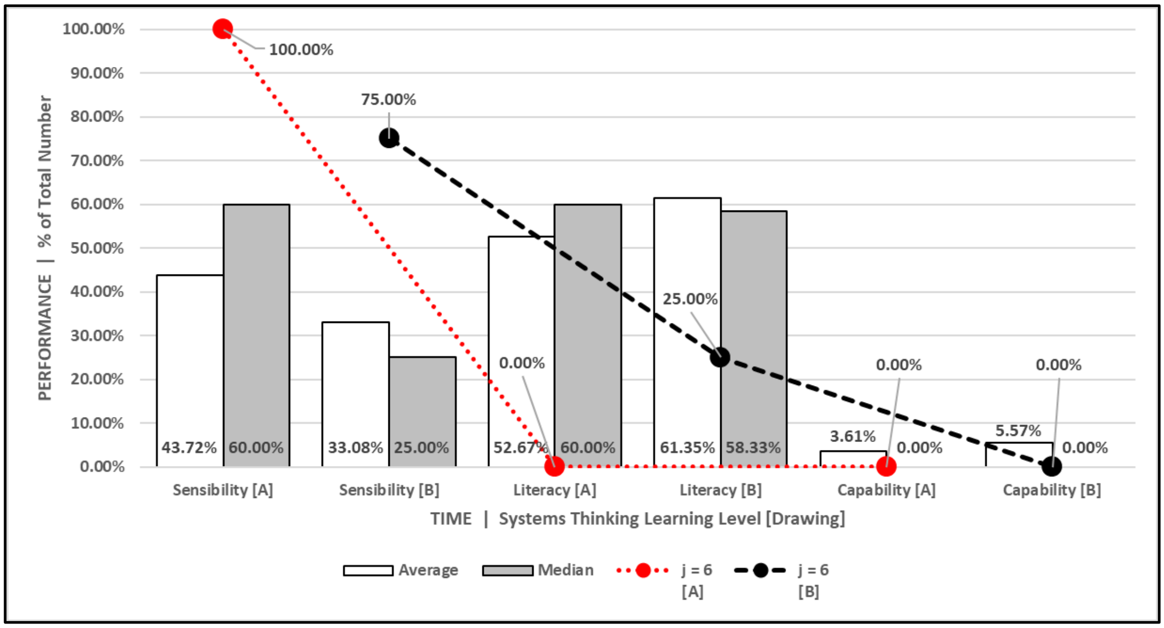

Figure 5-1: Systems Thinking Learning Model Example 1

Based on Figure 5-1, it can be concluded that student j = 6 identified all elements, interactions, and roles/purposes at the sensibility level (100.00%) and none at the other two levels of literacy and capability (0.00% for each) for Drawing A. For Drawing B this student still identified most items at the sensibility level (75.00%) and none at the capability level (0.00%), but they improved in the literacy level (25.00%). These percentages were determined by dividing the number of elements, interactions, and roles/purposes that this student identified for each learning level – which was three (3) for sensibility, one (1) for literacy, and zero (0) for capability in Drawing B – by the total number, which was four (4). Additionally, it can be concluded that this student still needs help to improve in their systems thinking learning because the plotted lines for both drawings exhibit the same negative slope from sensibility to capability. Ideally, the lines would be horizontal to represent a balanced combination of each systems thinking learning level. A horizontal or positively-sloped line would indicate that a student is thinking more at the literacy and capability levels and might be ready to move into rapid learning, the next phase of the systems thinking learning process.

Figure 5-2 illustrates another example of using this model to visually represent a student's systems thinking learning. This figure shows the results for student j = 11. Compared to student j = 6, student j = 11 demonstrated significant improvement in their systems thinking learning at the literacy level indicated by the 44.02% increase from Drawing A to Drawing B. In Drawing A this student predominantly identified items at a sensibility level and in Drawing B this student demonstrated more balanced learning between sensibility and literacy. From this model, it can be inferred that this student has reached the literacy level of systems thinking learning but that they need help to begin developing their thinking at a capability level, which was lacking in both drawings.

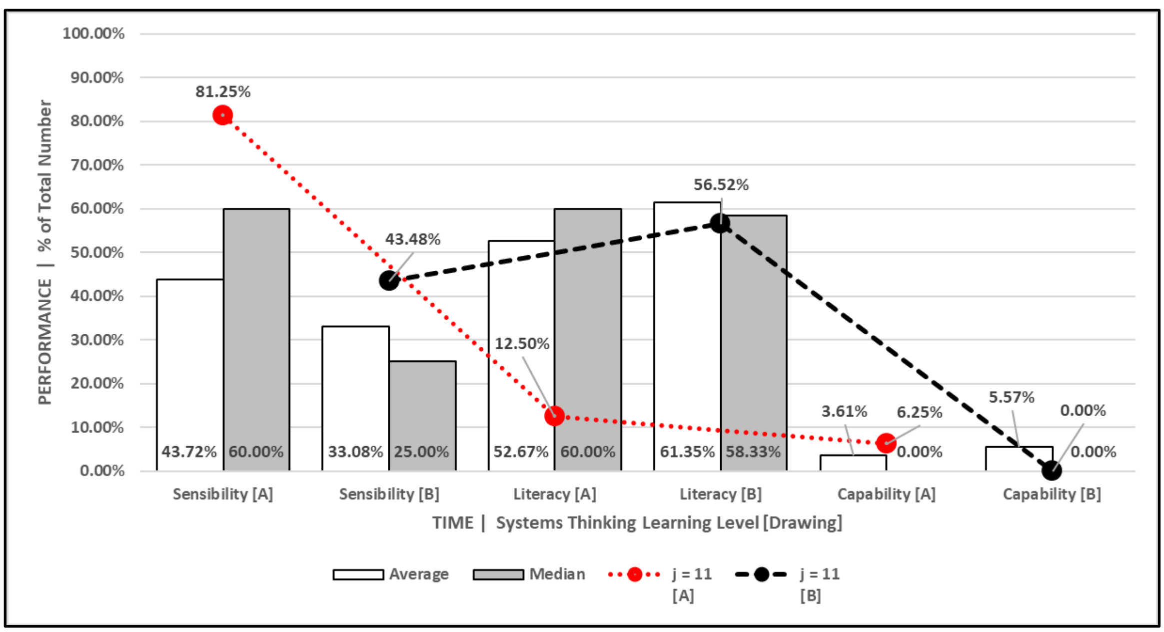

Figure 5-2: Systems Thinking Learning Model Example 2

5.3 Future Research Needs

Due to the exploratory design of this research, future research is needed to further develop the ideas and the results presented in this thesis. This research has only touched the surface of the systems thinking learning process by defining and measuring the initial learning phase for non-experts in the context of a fish-tank system. Future research efforts should focus on replicating the results of this research with different K-12 student populations, and even with other populations of people in the greater society, and for other example systems to build upon the methodology presented herein. Future research is also needed to expand the definitions and measurements of systems thinking learning to the next two phases proposed in this research as rapid learning and mastery learning.

Additionally, this research did not attempt to measure whether students retained the learning they had gained as a result of the experiment. The reinforcement of systems thinking learning throughout a student's educational journey is arguably more important than creating initial awareness about systems thinking concepts. Therefore, future research in this area should also focus on measuring systems thinking learning over longer periods of time to determine how to retain and reinforce systems thinking learning in education. All of the future research endeavors described here will continue to support the greater objective of growth in systems literacy and systems thinking education and will continue challenging the ways in which people think about the world the problems facing it.

Chapter 6

6 References

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Appendix A

7 Appendix A: ASEM Conference Paper

The following paper was published in the proceedings of the American Society for Engineering Management (ASEM) 2018 International Annual Conference in Coeur d'Alene, Idaho under the title, "A Proposed Methodology for Developing Systems Thinking Lessons By and For Non-Experts".

A PROSPOSED METHODOLOGY FOR DEVELOPING SYSTEMS THINKING LESSONS BY AND FOR NON-EXPERTS

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Abstract
Systems thinkers achieve expertise by learning from experts and reading existing systems thinking literature. This method is typically successful, if the learner is driven; however, this method does not work for everyone. This explains, in part, why systems thinking is not widely used. Many of today's complex problems can be solved using a systemic approach, but there are too many problems and not enough systems thinkers. Therefore, the need to expand systems education beyond the select few is critical. To foster widespread systemic thinking we must start reaching the next generation of thinkers in primary and secondary education (K-12). Unfortunately, the number of experts capable of teaching systems thinking is already small and the number of experts with the ability to teach K-12 students is even smaller. Additionally, the lack of systems thinking curriculum suitable for K-12 students presents another challenge. To address these challenges, the authors propose a systemic methodology, rooted in engineering management concepts, which will allow non-experts to create systems thinking lessons for K-12 audiences. The authors present the results on using the proposed methodology during a multi-year industrial engineering Capstone project, and discuss whether non-experts are capable of teaching systems thinking to other non-experts. The proposed methodology, while focused on developing systems thinking-centric lessons, has the potential to assist engineering managers with developing training modules for their work teams.

Keywords
Systems Thinking, Systems Thinking Education, Systems Thinking Lessons, Human-Activity Systems, Systems Literacy

Introduction
The typical approach employed to solve problems and study systems is known as reductionism. This approach breaks a problem or a system down into its constituent parts to gain an understanding of those parts, and then works backwards to understand the whole problem or system based on the parts. Reductionism can be successful in some cases, but it often fails when addressing complex problems in complex systems because a whole system is greater than the sum of its parts (Jackson, 2003). The alternative to the reductionism approach is a holistic approach. This approach views a whole system as the emergence of the interactions and relationships between parts. Once a system has emerged, it provides meaning to the parts and the interactions between those parts. This contrasts with the reductionism approach which allows the parts to provide meaning for the whole system. Holism is still interested in understanding the parts, but more attention is given to the network of relationships between the parts and how the interactions between those parts give rise to the whole system. (Jackson, 2003).

Systems thinking embraces this powerful holistic approach. Unfortunately, relatively few people have achieved expertise in systems thinking compared to other disciplines. This is due, in part, to the process of becoming a systems thinker. Similar to most other disciplines, a motivated learner achieves expertise in systems thinking by learning from an expert and reading existing literature on the subject to gain knowledge. Although this process is effective at producing more systems thinkers, it lacks the proliferation necessary to propagate systems thinking beyond the select few who are driven to learn. Most disciplines, like physics or biology for example, have thousands of experts available and learners (students) are exposed to these subjects during primary and secondary (K-12) education. The systems thinking discipline has significantly less experts available to teach those students who are interested and most students in K-12 education are not formally exposed to systems thinking content. To help solve complex problems the world needs more people who are simply aware of systems thinking concepts and who can use a holistic approach when solving problems. Therefore, a new methodology needs to be developed for teaching and learning systems thinking that will help increase the awareness and use of systems thinking concepts; the methodology should facilitate in spreading systemic sensibility. According to Ison & Shelley (2016), learning systems thinking goes through three phases: 1) Systemic sensibility – the ability to be aware of and appreciate systems, 2) Systems literacy – the ability to understand and teach systems thinking, and 3) Systems thinking in practice capability – the ability to use systems thinking to solve complex problems. Ison & Shelley further elaborate that although systemic sensibility is available to everyone, it is absent from the understandings and actions of many. This absence can be attributed to the inadequate or missing contexts (i.e. the systems thinking experts and curriculum) necessary for systemic sensibility to grow and be fostered within education and organizational life. Ison & Shelley argue that a shift from sensibility, or no sensibility, to capability is required to alter the current trajectory of complex problems facing organizations in the world today.

Those complex problems facing organizations today and in the future will require the attention of multiple generations of thinkers and problem solvers. To equip those generations with the skills necessary to handle these problems and practice systems thinking, the foundational skills of systemic sensibility must become more engrained at the primary and secondary education (K-12) level while leveraging current K-12 teachers' ability to reach this audience. This establishes the need to create a methodology for developing systems thinking lessons by and for non-experts. In this paper, a two-part conceptual model for such a methodology is presented.

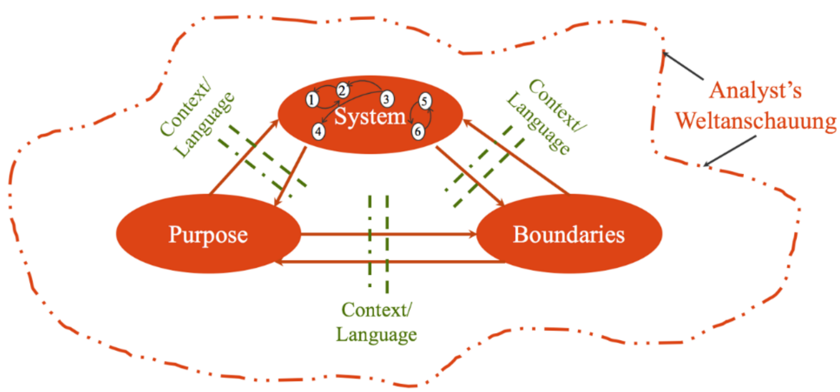
Background

In order to frame the conceptual model, it is necessary to understand the foundational concepts that inform its ontology. In this section, an overview of the foundational concepts and theories employed to develop the conceptual model are presented. In addition, the context that informed the development of this methodology will be presented.

What is a System?

Systems are found everywhere in life. Systems vary in type and include physical, biological, designed, abstract, social, and human-activity systems (Jackson, 2003). The conceptual model presented in this paper focuses on human-activity systems, which are intellectual constructs that express purposeful human activity (Checkland, 1981). For the purpose of this paper, a system is defined as "a perceived whole whose elements are interconnected and have a purpose in a given context" (Calvo-Amodio, Patterson, Smith, & Burns, 2014) and a boundary. A system is perceived, or defined, by an analyst (observer, stakeholder, manager, etc.) based on their weltanschauung, or world view. There is a dynamic relationship between the system, its boundaries, and its purpose within the context allowing the analyst to define what the system is to them. This dynamic relationship means the analyst's weltanschauung changes over time as their knowledge about the system and its context grows. Thus, a system is what the analyst defines as a system. Exhibit 1 presents a graphical representation for a human-activity system based on the definition provided.

Exhibit 1. Definition of a Human-Activity System (adapted from Calvo-Amodio et al., 2014)



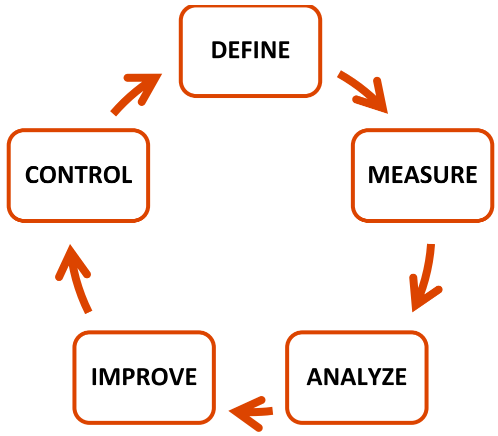
What is Systems Thinking?

Systems thinking is a particular way of thinking about the world (Checkland, 1981). This type of thinking is a holistic approach to studying systems (Jackson, 2003) and uses the idea of systems to try and understand complexity in the world. Complex problems, the ones for which a reductionist approach is often ineffective, combine many issues and cross many disciplines to create varying perspectives. Systems thinking attempts to provide a common perspective by aligning how we think real-world systems work with how they actually work (Cabrera, 2015). For the purpose of this paper, systems thinking is defined as "an interdisciplinary and holistic approach to understanding human-activity systems" (Solberg, Calvo-Amodio, Ng, & Reintjes, 2016).

DMAIC

The five-step, systematic problem solving procedure called DMAIC, presented in Exhibit 2, is widely used to identify the root causes of problems and implement sustainable solutions that improve process and system performance (Montgomery, 2013). The five steps of DMAIC correspond to each letter in the acronym and stand for: 1) Define – identify the problem and opportunity for improvement, 2) Measure – evaluate the current state, 3) Analyze – measure the current state and determine cause-and-effect relationships, 4) Improve – implement changes to correct the problem and capitalize on the opportunity, and 5) Control – ensure the changes that are implemented are sustained.

Exhibit 2. The DMAIC Process (adapted from Montgomery, 2013)



Soft Systems Methodology

Peter Checkland (1981) developed soft systems methodology (SSM) as a seven-stage cyclical learning system. The seven stages are summarized here:

1. Consider the problem situation (SSM1)
2. Express the problem situation (SSM2)
3. Formulate root definitions of relevant systems (SSM3)
4. Create conceptual models (SSM4)
5. Compare conceptual models to the real-world problem (SSM5)
6. Define possible and feasible changes (SSM6)
7. Take action to improve the problem situation (SSM7)

Steps 1, 2, 5, 6, and 7 are considered real-world activities which involve people as part of the problem situation. Situation in this context is used to define the domain where the problem lies. Steps 3 and 4 are considered systems thinking activities. A popular method of SSM is known as CATWOE which defines the six characteristics included in the root definition of stage 3. CATWOE allows a system analyst to identify key stakeholders and consider multiple viewpoints (Checkland, 1981). Each letter of the CATWOE acronym stands for a separate characteristic:

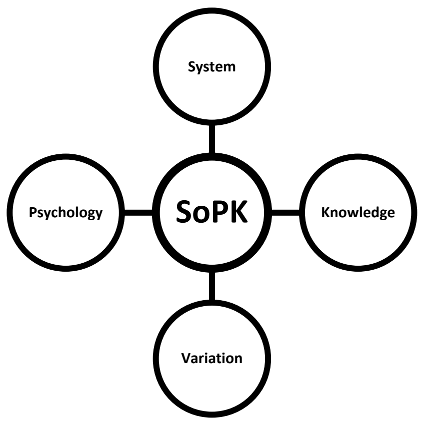
- A *Customer (C)* is a stakeholder who benefits from or is a victim of the system.
- An *Actor (A)* is a stakeholder who carries out activities in the system.
- A *Transformation (T)* describes the means by which defined inputs are transformed into defined outputs.
- The *Weltanschauung (W)*, or world view, makes the root definition meaningful.
- An *Owner (O)* is a stakeholder who can modify or destroy the system.
- The *Environmental (E)*, or external, constraints are given for the system.

System of Profound Knowledge

Deming (1994) proposed the system of profound knowledge (SoPK) as a theory to better understand organizations and systems by embracing an outside view. The theory argues that a system cannot understand itself and therefore requires an outside perspective to inform how transformations can foster new understanding. The outside view of SoPK consists of four interdependent, complementary parts as presented in Exhibit 3 and summarized here:

- **Appreciation for a system –** Deming (1994) argues that a system must have an aim, or a purpose, otherwise no system can be defined. Appreciation for the system involves understanding both the interdependence and obligation of each part in the system.
- **Theory about variation –** "Life is variation" (Deming, 1994). Knowledge of variation requires the analyst of a system to understand both the normal and non-normal (special) causes of variation. If a system is stable, then its behavior can be predicted.
- **Theory of knowledge –** "Management is prediction" (Deming, 1994). Knowledge is formed from theory. Without theories, and the revision of those theories, no new knowledge can be generated and thus no learning.
- **Psychology –** Understanding psychology helps to better understand people (Deming, 1994) and acknowledge their differences. This perspective is crucial to the outside view concept of SoPK and for understanding any system, especially a human-activity system.

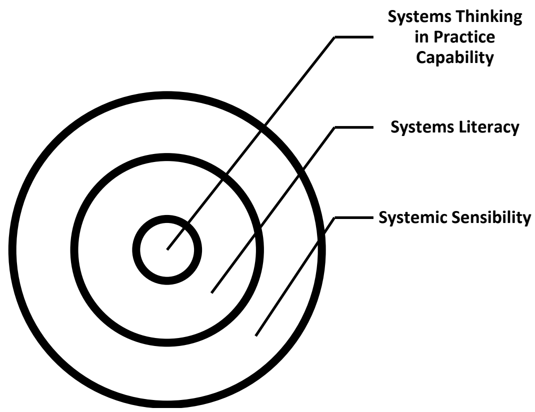
Exhibit 3. The System of Profound Knowledge (adapted from Deming, 1994)



A Path to Systems Literacy

Crowell (1992) appears to have first introduced the idea of systems literacy. Crowell describes a system as "a way of looking at the world", and therefore, systems literacy is the capability of understanding and communicating about the world using systems. Tuddenham (2017) has expanded upon this idea and describes Systems Literacy as an ongoing effort to foster greater awareness and understanding about systems throughout the world. This effort strives to pioneer a more sustainable future by leveraging increased awareness and understanding of systems in the world to facilitate more informed decisions and communication using systems approaches. This vision of systems literacy from Crowell and Tuddenham match well with the ideas of Ison & Shelley (2016) who propose that systems thinking learning goes through three phases, as discussed earlier, and presented graphically in Exhibit 4. Many people lie outside or on the outer border of systemic sensibility (i.e. non-experts in systems thinking who generally lack awareness and understanding about systems). The goal of Systems Literacy is to increase the number of people who are aware of and understand systems, and who can then teach others to cause a proliferation of systems thinkers in the world. The three-phase systems thinking learning progression idea proposed by Ison provides a roadmap for achieving that goal.

Exhibit 4. Nested Systemic Relationship between Systemic Sensibility, Systems Literacy, and Systems Thinking in Practice Capability (adapted from Ison & Shelley, 2016)



Context for Developing Methodology

The work to create a methodology for developing systems thinking lessons by non-experts for non-experts has been influenced primarily through industrial engineering Capstone senior design course projects at Oregon State University (OSU). The Capstone course provides these senior industrial engineering students with a systematic process using the concepts of DMAIC (Montgomery, 2013) and SSM (Checkland, 1981) combined with the systemic approach of SoPK (Deming, 1994) to guide the completion of assigned projects. Two of these Capstone projects, one in 2016-17 and the other in 2017-18, sought to foster greater systemic sensibility among the next generation of thinkers and problem solvers by developing systems thinking lessons for the Science and Math Investigative Learning Experiences (SMILE) Program. SMILE is a pre-college program at OSU that helps lower-income, ethnic-minority, and educationally-underrepresented middle and high school students in rural Oregon communities gain the skills and attitudes necessary to pursue higher educational opportunities in science, technology, engineering, and math fields.

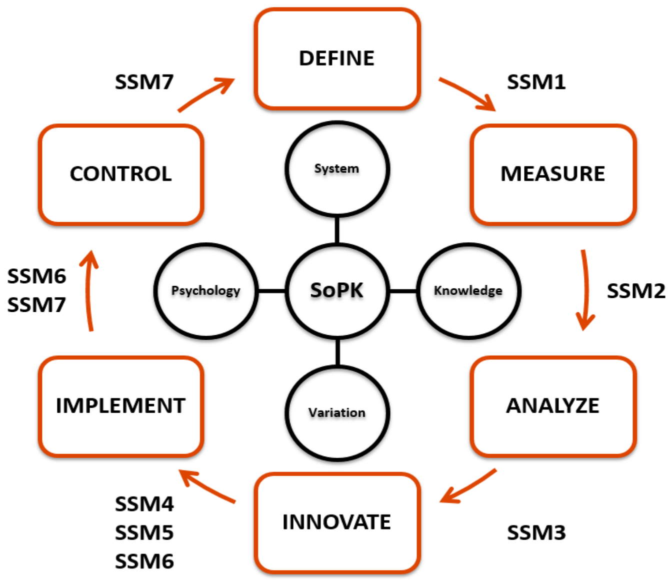
For both of these Capstone projects, CATWOE (Checkland, 1981) was critical for defining the key stakeholders and for viewing the development of systems thinking lessons from multiple perspectives. The customers (C) are the students and the educators, or teachers, who will learn from the lessons developed. The actors (A) are the educators, or teachers, who will teach the lessons. The transformation (T) represents the SMILE Program which provides the means to transform non-experts (students and teachers) in systems thinking into systems thinkers who have at least systemic sensibility. The weltanschauung (W), or world view, is the three-phase systems thinking learning progression idea proposed by Ison & Shelley (2016). The owner (O) is also the SMILE Program, or the sponsor. Lastly, the environmental (E) constraints are the educational standards and sponsor requirements that guide the development of the lessons. Ideally, if the situation allows, the system analyst (the person developing lessons) should be external to the system and be a non-expert in systems thinking. This relates back to the SoPK by Deming (1994) which emphasizes the outside view as a key component to understanding the system for which lessons are being developed for. Also, a non-expert is better able to relate to other non-experts when developing lessons. For example, the analyst could be a teacher or educator developing lessons for other teachers or educators in the system of interest.

Conceptual Model

Having established the foundational concepts behind this methodology, the conceptual model for developing systems thinking lessons by and for non-experts can now be presented. The model is represented in two parts. The first part of the model presents the methodology for developing systems thinking lessons and is to be used by the system analyst. The second part of the model presents the methodology for systems thinking learning and is to be used by the system analyst to inform the development of lessons.

The first part of the model couples the systematic processes of DMAIC and soft systems methodology (SSM) with the systemic approach of the system of profound knowledge (SoPK) for the development of systems thinking lessons (Exhibit 5). The DMAIC process forms the systematic backbone for this part of the model. DMAIC is combined with soft systems methodology (SSM) to form a more robust, systems-based process. In order to better combine DMAIC and SSM, the DMAIC process has been modified to DMAIIC based on experience gained from the design and management of the Capstone senior design course. The first letter "I" stands for Innovate – to develop solution innovations or alternatives – and the second letter "I" now stands for Implement – to select an innovation alternative or solution to implement. These two changes allow for better alignment with stages 4, 5, and 6 from SSM where conceptual models, or innovation alternatives, are created and compared to determine the best possible and feasible solution to the problem. Additionally, the integration of CATWOE from SSM into the Define, Measure, and Analyze steps of DMAIIC provides a systems-based method for identifying key stakeholders and multiple viewpoints to inform the lesson development process. The SoPK provides the systemic component of the model and is embedded at each of the steps and stages of DMAIIC and SSM respectively. SoPK strongly influences the beginning of the lesson development process when the system analyst is learning about their system and defining the requirements and current state of that system. SoPK also strongly influences the Innovate step of the DMAIIC process where innovation alternatives should be developed that emphasize each of the four SoPK perspectives.

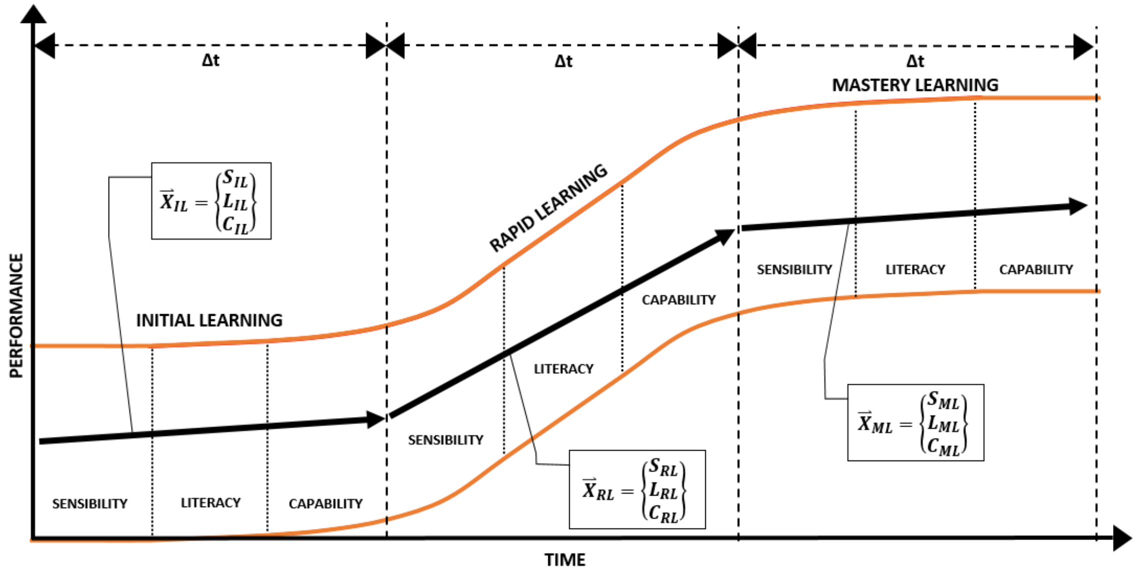
Exhibit 5. Systems Thinking Lesson Development Model



The second part of the conceptual model presents a way in which to measure systems thinking learning progression along an S-shaped curve (Exhibit 6). There are three distinct phases of systems thinking learning characterized by the S-shape. Initial learning (IL) is the first phase and represents the period during which basic concepts of systems thinking are introduced. Rapid learning (RL) is the second phase and represents the period during which basic concepts become better understood through experience and practice with systems. Mastery learning (ML) is the third phase and represents the period of stabilization attributed with reaching expertise in systems thinking. Within each phase i, a learner will progress through each of the three systems thinking phases (sensibility (S), literacy (L), and capability(C)) as defined by the vector $\vec{X}$ shown in Eq. (1). The authors believe that this vector must be aligned with a pre-determined eigenvector dependent on the desired learning progression for an individual learner. For each phase i of learning, a different eigenvector can exist, as an individual learner's progression through the phases might vary because for different Δt the shape of the learning curve will change. This vector will measure where a learner is in the systems thinking progression to help inform the development of lessons by the system analyst. The validation of this model will be the primary focus of future work for this research.

$$\vec{X}_i = \begin{Bmatrix} S_i \\ L_i \\ C_i \end{Bmatrix} \quad (1)$$

Exhibit 6. Systems Thinking Learning Model



Preliminary Results

The preliminary results from the two industrial engineering Capstone senior design course projects have shown that system analysts (engineering students who are non-experts in systems thinking) were successful in developing systems thinking lessons for non-experts. The goal for both projects was to develop systems thinking lessons that increase systemic sensibility among the target population of middle to high school students in the SMILE Program using the methodology presented in the first part of the conceptual model. The first Capstone project in 2016-17 produced four interdependent systems thinking lessons. The four lessons focused on the systems thinking concepts of systems, system hierarchies, emergence, and feedback loops. The lesson on emergence was demonstrated and validated during a SMILE teacher workshop. Thirty-six teachers provided their feedback on a six-point Likert scale, from strongly agree (6) to strongly disagree (0), to five statements about the lesson. The results are shown in Exhibit 7. The key takeaways from these results were that teachers overall would feel comfortable teaching the lesson to their students (Statement 1) and that their students would understand the learning objectives of the lesson (Statement 5). As part of the second Capstone project in 2017-18, a survey was developed to follow-up with SMILE teachers about their use of the four lessons developed by the Capstone project team in 2016-17. Nineteen teachers responded to the survey and about 37% of those teachers had taught at least one of the lessons on systems thinking to their SMILE club students.

Exhibit 7. Teacher Workshop 2017 Questionnaire Results for Emergence Lesson (36 responses)

#	Statement	Median	Mean	Std. Dev.
1	I feel comfortable teaching this lesson with the provided background material and activity instructions.	5	5.25	0.55
2	This lesson allows me to meet Next Generation Science Standards (NGSS) requirements and provide cross-cutting concepts.	5	4.94	0.73
3	Most of my students will find the lesson activity interesting and engaging.	5	5.31	0.71
4	I can afford the cost and time to acquire materials and prepare for this lesson.	6	5.61	0.55
5	I would expect most of my students to understand the learning objectives after completing this lesson.	5	4.86	0.72

The second Capstone project also produced two more systems thinking lessons. These lessons focused on the systems thinking concepts of patterns and perspectives. In both Capstone projects, the lessons were developed by undergraduate industrial engineering students considered to be non-experts in systems thinking at the beginning of the project. The result of the development of these six lessons on systems thinking suggests that non-experts in systems thinking are capable of learning systemic sensibility, and some systems literacy, in order to develop lessons. Although learning of systems thinking was not objectively measured, the achievement of systemic sensibility by both SMILE teachers and students was observed during demonstrations of the lessons in both Capstone projects. These results suggest that the non-experts in systems thinking who had acquired systemic sensibility (i.e. the undergraduate engineering students), were capable of teaching the lessons in systems thinking to other non-experts. However, further research and data collection is necessary to validate these initial findings.

Conclusion and Future Work

A systemic methodology rooted in engineering management concepts has been presented which allows non-experts in systems thinking to develop lessons and teach those lessons to other non-experts. The goal of the proposed methodology is to foster greater systemic sensibility, or awareness and understanding of systems, among all people. As Ison & Shelley (2016) claim, systemic sensibility is available to all people, but the contexts necessary for this sensibility to grow are inadequate or missing. The proposed methodology addresses this problem by first, providing a way to increase the amount of systems thinking content for K-12 audiences through a systematic process guided by a systemic approach. Second, it provides a way to increase the number of people who have sensibility and can teach systems thinking to others by measuring systems thinking learning through the three phases of sensibility, literacy, and capability.

Future research will be focused in three areas. First, the first part of the conceptual model will be refined to better explain how to develop systems thinking lessons. The current model focuses more on the overall process of developing systems thinking lessons and lacks some details that will help system analysts develop successful lessons. Second, the variables used to measure the learning vectors in the second part of the conceptual model need to be determined. These variables will also be used to inform the pre-determined eigenvectors that guide how an individual learner should progress through the S-shaped curve of systems thinking learning. Third, a validation plan will be developed to further test both parts of the conceptual model presented in this paper. This validation will, in part, be conducted during the next Capstone senior design course project with SMILE at Oregon State University in 2018-19.

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Jay Well is the Assistant Director of the SMILE Program at Oregon State University. Through his work at SMILE he seeks to establish a pathway to success for students throughout their careers from K-12, to college, and into future careers in science, technology, engineering, and math (STEM) fields. Jay has served as the project sponsor for the industrial engineering Capstone projects over the last five years.

Appendix B

8 Appendix B: Element Classification Tables

The forty-nine (49) elements that were defined for a fish-tank system prior to analyzing the data are presented in Table 8-1.

The classifications for each of the forty-nine (49) elements defined for a fish-tank system prior to analyzing the data are presented in Table 8-2.

The eleven (11) additional elements that were defined for a fish-tank system while analyzing the data are presented in Table 8-3.

The classifications for each of the eleven (11) additional elements that were defined for a fish-tank system while analyzing the data are presented in Table 8-4.

Table 8-1: Fish-Tank System Elements (defined prior to analysis)

Element Name (alphabetical)	**Element Description & Element's Role / Purpose in Fish-Tank System (Mills, 1987)**
Air and/or Bubbles	A more common name for Oxygen (O_2); Produced by the air pump and via respiration from fish and other animals.
Air or Water Pump	An air pump is a porous device through which air is passed; Also called an aerator, an air stone, or a diffusor; Produces air bubbles in the water for aeration (the ventilation of the water which facilitates intake of oxygen and the expulsion of carbon dioxide). A water pump is a device that moves water through the tank.
Algae	A green colored plant; Can be used to make the fish tank more decorative; A food source for herbivorous fish; Absorbs minerals from the water; Consumes waste products like Nitrate (NO_3^-).
Ammonia (NH_3)	The first byproduct of decaying organic material; An "invisible" waste product excreted by fish; Feeds aerobic (oxygen-loving) bacteria.
Bacteria	Microscopic organisms; Decompose organic matter and waste products.
Bio-filter	A natural type of filter; Cleans the fish tank water via circulation allowing bacteria to filter the water.
Broken / Dirty Filter	Supposed to fulfilling the role of a filter; If left unchecked, it can be an underlying cause of dirty or green water.
Carbon Dioxide (CO_2)	A byproduct of respiration by fish and other organisms; Feeds plants and algae.
Coral	Used for decoration; Provides a good surface for algae to grow on.
Dead Organisms	Includes dead fish or animals; Can be broken down as a food source for bacteria and fungi.
Denitrifying Bacteria	Anaerobic, oxygen-hating type of bacteria; Converts excess nitrate into free Nitrogen gas.
Dirt, Dust, and Debris	Visible particles present in the water; Removed by a filter or a filtration system.
Electricity	Provides power for the heater, lights, pumps, etc.
Excess Fish Waste Products	Includes both fish waste and ammonia, both excreted by fish as waste products; Excess waste products are a higher than normal amount; Can be an underlying cause of dirty or green water.
Filter	A device which cleans the fish tank water; May include filter tubes, a filter/tube screen, and any filter medium (such as activated carbon/charcoal).
Filter Feeder Fish	A special type of fish that sifts the water for microscopic food; Helps to keep the tank and water clean.

Element Name (alphabetical)	**Element Description & Element's Role / Purpose in Fish-Tank System (Mills, 1987)**
Filtration System	A system that may contain a filter, filter tubes, a filter/tube screen, and any filter medium (such as activated carbon/charcoal); Removes visible particles from the water; Provides healthy water conditions for fish and other animals.
Fish	The focal point of the system; There is no fish-tank system without a fish; Fish can be marine, freshwater, tropical, etc.
Fish Food	A nutrient and energy source eaten by fish; Feeds the fish.
Fish Net	A tool used to safely add or remove fish from the fish tank.
Fish Waste	A "visible" waste product excreted by fish, mostly excrement; Can be broken down as a food source for bacteria and fungi.
Free Nitrogen Gas (N_2)	The product of the conversion of Nitrates (NO_3^-) by anaerobic bacteria; Vented from the fish-tank system since it is not needed.
Fungi	Microscopic organisms; Decompose organic matter and waste products.
Green Water	Water that has excess algae bloom present.
Heater	A submersible device controlled by the thermostat to heat the water.
Human	Maintains the fish-tank system; Views the fish tank as "beautiful" or "nice to look at".
Impeller	An electrically-driven propeller; Used to produce water flow through a filter, filtration system, water pump, or the fish tank.
Lighting / Lights	Simulates a "real" aquatic environment; Promotes fish well-being; Encourages algae growth and therefore, can be an underlying cause of green water if used excessively or unchecked.
Nitrate (NO_3^-)	A less toxic ammonium compound produced by Nitrate bacteria from Nitrite (NO_2^-); Can also be broken down again by denitrifying bacteria into free Nitrogen gas (N_2).
Nitrate Bacteria	Anaerobic, oxygen-hating bacteria such as Nitrobacter; Convert Nitrite (NO_2^-) into Nitrate (NO_3^-).
Nitrite (NO_2^-)	A slightly less toxic ammonium compound; Feeds Nitrate bacteria to be broken down into Nitrate (NO_3^-).
Nitrite Bacteria	Aerobic, oxygen-loving bacteria such as Nitrosomonas; Convert ammonium (NH_3) into Nitrite (NO_2^-).
Oxygen (O_2)	A byproduct of photosynthesis carried out by plants and algae; Supports Nitrite bacteria, fish and other organisms in the fish tank.
Ornaments / Decorations	Any item used purely for decorative purposes in the fish tank. Includes a fish house/home.
Other Animals	Additional aquatic animals other than fish; May include snails, shrimp, crabs, etc.
Plant Fragments	Detached pieces of plants in the water; Broken down as a food source for bacteria and fungi.

Element Name (alphabetical)	**Element Description & Element's Role / Purpose in Fish-Tank System (Mills, 1987)**
Plants	Includes grass, seaweed, etc.; A food source for herbivorous fish; Can be used as purely decoration; Provide a hiding and breeding place for fish; Provides comfort for fish; Provide oxygen (O_2) in the water as a result of photosynthesis; Remove carbon dioxide (CO_2) from the water; Promote helpful bacteria growth; Remove Nitrates (NO_3^-) from the water; Improve overall water quality.
Rocks	A large solid structure (not to be confused with substrate); Can be used as purely decoration; Provide shelter and hiding places for fish.
Silicone	A bonding or sealing agent for the glass walls of the fish tank.
Substrate	Includes one of, or a combination of, the following solid structures: gravel, pebbles, soil, sand, crushed coral, etc.; Can be viewed purely as decoration; Provides fish with a means to bury themselves in to sleep or to sift through for food; Provides a surface area for bacteria to grow.
Sunlight	Naturally occurring light; Promotes fish well-being; Encourages algae growth and therefore, can be an underlying cause of green water if not controlled.
Tank	Usually constructed out of glass; The boundary of the system which separates the system from its environment; To hold all the elements inside the system boundary together.
Tank Cover (Lid)	Covers the fish tank to keep foreign objects from entering the tank; Protects against condensation and evaporation; Can house lights.
Tank Stand	A structure that can support the weight of the fish-tank system.
Tank Wall Scraper	A tool used to clean algae growth off the walls of the fish tank.
Thermometer	A device to measure water temperature and relay information to the thermostat.
Thermostat	Controls the supply of electricity to the heater based on readings from the thermometer.
Uneaten Fish Food	Fish food that is not eaten by fish; Can be eaten by filter feeder fish or broken down as a food source for bacteria and fungi.
Water	Keeps the living organisms in the tank alive; Maintains system balance (i.e. sudden changes to the water can greatly affect system behavior).

Table 8-2: Fish-Tank System Element Classifications

(1) Element Name (alphabetical); (2) Concrete or Conceptual; (3) Internal or External; (4) Essential; (5) Underlying; (6) Sub-System; (7) Essential, Secondary, or Advanced; (8) Systems Thinking Learning Level Classification							
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
Air and/or Bubbles	Concrete	Internal	No	No	No	Secondary	Literacy
Air or Water Pump	Concrete	Internal	No	No	No	Secondary	Literacy
Algae	Concrete	Internal	No	No	No	Secondary	Literacy
Ammonia (NH_3)	Conceptual	Internal	No	No	No	Advanced	Capability
Bacteria	Conceptual	Internal	No	No	No	Advanced	Capability
Bio-filter	Concrete	Internal	No	No	No	Secondary	Literacy
Broken / Dirty Filter	Concrete	Internal	No	Yes	No	Advanced	Capability
Carbon Dioxide (CO_2)	Conceptual	Internal	No	No	No	Advanced	Capability
Coral	Concrete	Internal	No	No	No	Secondary	Literacy
Dead Organisms	Concrete	Internal	No	Yes	No	Advanced	Capability
Denitrifying Bacteria	Conceptual	Internal	No	No	No	Advanced	Capability
Dirt, Dust, and Debris	Concrete	Internal	No	No	No	Secondary	Literacy
Electricity	Conceptual	External	No	No	No	Advanced	Capability
Excess Fish Waste Products	Concrete	Internal	No	Yes	No	Advanced	Capability
Filter	Concrete	Internal	No	No	No	Secondary	Literacy
Filter Feeder Fish	Concrete	Internal	No	No	No	Secondary	Literacy
Filtration System	Concrete	Internal	No	No	Yes	Advanced	Capability
Fish	Concrete	Internal	Yes	No	No	Essential	Sensibility
Fish Food	Concrete	Internal	No	No	No	Secondary	Literacy
Fish Net	Concrete	External	No	No	No	Secondary	Literacy
Fish Waste	Concrete	Internal	No	No	No	Secondary	Literacy
Free Nitrogen Gas (N_2)	Conceptual	Internal	No	No	No	Advanced	Capability
Fungi	Conceptual	Internal	No	No	No	Advanced	Capability
Green Water	Concrete	Internal	No	No	No	Secondary	Literacy
Heater	Concrete	Internal	No	No	No	Secondary	Literacy
Human	Concrete	External	No	No	No	Secondary	Literacy
Impeller	Concrete	Internal	No	No	No	Secondary	Literacy

(1) Element Name (alphabetical); (2) Concrete or Conceptual; (3) Internal or External; (4) Essential; (5) Underlying; (6) Sub-System; (7) Essential, Secondary, or Advanced; (8) Systems Thinking Learning Level Classification							
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
Lighting / Lights	Concrete	External	No	Yes	No	Advanced	Capability
Nitrate (NO_3^-)	Conceptual	Internal	No	No	No	Advanced	Capability
Nitrate Bacteria	Conceptual	Internal	No	No	No	Advanced	Capability
Nitrite (NO_2^-)	Conceptual	Internal	No	No	No	Advanced	Capability
Nitrite Bacteria	Conceptual	Internal	No	No	No	Advanced	Capability
Oxygen (O_2)	Conceptual	Internal	No	No	No	Advanced	Capability
Ornaments / Decorations	Concrete	Internal	No	No	No	Secondary	Literacy
Other Animals	Concrete	Internal	No	No	No	Secondary	Literacy
Plant Fragments	Concrete	Internal	No	No	No	Secondary	Literacy
Plants	Concrete	Internal	No	No	No	Secondary	Literacy
Rocks	Concrete	Internal	No	No	No	Secondary	Literacy
Silicone	Concrete	Internal	No	No	No	Secondary	Literacy
Substrate	Concrete	Internal	No	No	No	Secondary	Literacy
Sunlight	Concrete	External	No	Yes	No	Advanced	Capability
Tank	Concrete	Internal	Yes	No	No	Essential	Sensibility
Tank Cover (Lid)	Concrete	External	No	No	No	Secondary	Literacy
Tank Stand	Concrete	External	No	No	No	Secondary	Literacy
Tank Wall Scraper	Concrete	External	No	No	No	Secondary	Literacy
Thermometer	Concrete	Internal	No	No	No	Secondary	Literacy
Thermostat	Concrete	External	No	No	No	Secondary	Literacy
Uneaten Fish Food	Concrete	Internal	No	Yes	No	Advanced	Capability
Water	Concrete	Internal	Yes	No	No	Essential	Sensibility

Table 8-3: Additional Fish-Tank System Elements (defined during analysis)

Element Name (alphabetical)	Element Description & Role / Purpose in Fish Tank System
Battery	Provides power for the heater, lights, pumps, etc.
Bucket	A tool used to add or remove water from the fish tank.
Cat	An animal external to the fish-tank system; May try to get fish from the tank.
Chemicals	Substances used to maintain fish-tank system balance and/or water health.
Electrical Cord/Outlet	The electrical cord transports electricity from the electrical outlet to a device; the electrical outlet is a place to plug in an electrical cord.
Kool-Aid Packet	An element outside the fish-tank system that a human could pour into the water to turn it green. Therefore, this could be an underlying cause of green water.
Nuclear Waste	An element outside the fish-tank system that could somehow end up in the tank and turn the water green. Therefore, this could be an underlying cause of green water.
Oil	Naturally-occurring substances from fish and other animals.
Smoke	A potential output from a broken filter or other broken mechanical devices.
Trash	An element added from outside of the system; Can kill fish and other animals if eaten.
Tree	A “plant” that is external to the fish-tank system; Blocks sunlight and keeps the fish tank in the shade.

Table 8-4: Additional Fish-Tank System Element Classifications

(1) Element Name (alphabetical); (2) Concrete or Conceptual; (3) Internal or External; (4) Essential; (5) Underlying; (6) Sub-System; (7) Essential, Secondary, or Advanced; (8) Systems Thinking Learning Level Classification							
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
Battery	Concrete	External	No	No	No	Secondary	Literacy
Bucket	Concrete	External	No	No	No	Secondary	Literacy
Cat	Concrete	External	No	No	No	Secondary	Literacy
Chemicals	Concrete	External	No	No	No	Secondary	Literacy
Electrical Cord/Outlet	Concrete	External	No	No	No	Secondary	Literacy
Kool-Aid Packet	Concrete	External	No	Yes	No	Advanced	Capability
Nuclear Waste	Concrete	External	No	Yes	No	Advanced	Capability
Oil	Concrete	Internal	No	No	No	Secondary	Literacy
Smoke	Concrete	External	No	No	No	Secondary	Literacy
Trash	Concrete	External	No	No	No	Secondary	Literacy
Tree	Concrete	External	No	No	No	Secondary	Literacy

Appendix C

9 Appendix C: Glossary of Variables

All of the variables used in this thesis are presented and described in Table 9-1.

Table 9-1: Glossary of Variables

Variable	Description / Definition
Subscript Variables	
i	The experimental tests = drawings = [A, B, BA], where: A = Drawing A (warm-up activity drawing); B = Drawing B (systems thinking activity drawing); BA = Drawing B - Drawing A (difference between the drawings)
j	The students in the experiment = 1, 2, …, n_i
k	The systems thinking concepts = [Elements (E), Interactions (I), Roles/Purposes (R)]
l	The systems thinking learning levels = [Sensibility (S), Literacy (L), Capability (C)]
T	Used to represent the total (*T*) in number (*x*) or score (*z*) for a specific systems thinking concept (*k*) across all systems thinking learning levels (*l*) *OR* Used to represent the total (*T*) in number (*x*) or score (*z*) for all systems thinking concepts (*k*) at a specific systems thinking learning level (*l*) *OR* Used to represent the total (*T*) in number (*x*) or score (*z*) for all systems thinking concepts (*k*) across all systems thinking learning levels (*l*)
w	Group number in the ANOVA for groups test (see description in section **Error! Reference source not found.**)
v	Student number in each group for the ANOVA for groups test (see description in section **Error! Reference source not found.**)
Other Variables	
α	Alpha = the significance level for hypothesis tests
μ	Mu = the mean for all students *j* = 1, 2, …, n_i
σ	Sigma = the standard deviation
σ^2	Sigma squared = the variance; also = the variation within groups (used for the ANOVA for groups test described in section **Error! Reference source not found.**)
σ_τ^2	Sigma tau squared = the variation between groups

Variable	Description / Definition
	(used for the ANOVA for groups test described in section **Error! Reference source not found.**)
R_j	The rank of the paired difference d_j in the Wilcoxon signed ranks test (see description in section 3.2.5.3)
S	Sample standard deviation
S^2	Sample variance
n_i	The number of students for each drawing *i*
$n_{BA}{}'$	The number of paired samples for drawing *i* = BA that remain after omitting paired samples equal to zero in the Wilcoxon signed ranks test (see description in section 3.2.5.3)
n_w	The number of students in each group in the ANOVA for groups test (see description in section **Error! Reference source not found.**)
N	The total number of students (*v*) across all groups (*w*) in the ANOVA for groups test (see description in section **Error! Reference source not found.**)
n_0	The estimator of sample size per group for an unbalanced design in the ANOVA for groups test (see description in section **Error! Reference source not found.**)
a	The number of levels (groups) in the ANOVA for groups test (see description in section **Error! Reference source not found.**)
d	The paired difference (*d*) between drawings B and A
$\bar{d}$	The average paired difference (*d*) between Drawings B and A
$\tilde{d}$	The median paired difference (*d*) between Drawings B and A
d_j	The paired difference (*d*) between Drawings B and A for student *j*
d_{wv}	The paired difference (*d*) between Drawings B and A for student *v* in group *w* in the ANOVA for groups test (see description in section **Error! Reference source not found.**)
F	Familiarity rating of fish-tank systems (provided by student)
Variables Used for Number of (*x*)	
x	The number (*x*) of systems thinking concepts identified
$\bar{x}$	x bar = The average number (*x*) of systems thinking concepts identified
$\tilde{x}$	x tilde = The median number (*x*) of systems thinking concepts identified
x_{ijkl}	The number (*x*) of a specific systems thinking concept *k* [Elements (E) or Interactions (I) or Roles/Purposes (R)] identified for drawing *i*, student *j*, and systems thinking learning level *l*
x_{ijkT}	The total (*T*) number (*x*) of a specific systems thinking concept *k* [Elements (E) or Interactions (I) or Roles/Purposes (R)] identified for drawing i and student *j* across all systems thinking learning levels *l*
x_{ijlT}	The total (*T*) number (*x*) of all systems thinking concepts *k* [Elements (E) + Interactions (I) + Roles/Purposes (R)] identified for drawing *i*, student *j*, and systems thinking learning level *l*

Variable	Description / Definition
x_{ijT}	The total (*T*) number (*x*) of all systems thinking concepts *k* [Elements (E) + Interactions (I) + Roles/Purposes (R)] identified for drawing *i* and student *j* across all systems thinking learning levels *l*
Variables Used for Score (*z*)	
z	The score (*z*) for systems thinking concepts identified
$\bar{z}$	z bar = The average score (*z*) for systems thinking concepts identified
$\tilde{z}$	z tilde = The median score (*z*) for systems thinking concepts identified
z_{ijkl}	The score (*z*) for a specific systems thinking concept *k* [Elements (E) or Interactions (I) or Roles/Purposes (R)] identified for drawing *i*, student *j*, and systems thinking learning level *l*
z_{ijkT}	The total (*T*) score (*z*) for a specific systems thinking concept *k* [Elements (E) or Interactions (I) or Roles/Purposes (R)] identified for drawing *i* and student *j* across all systems thinking learning levels *l*
z_{ijT}	The total (*T*) score (*z*) of all systems thinking concepts *k* [Elements (E) + Interactions (I) + Roles/Purposes (R)] identified for drawing *i* and student *j* across all systems thinking learning levels *l*
$d_{z\,jT}$	The paired difference in total (*T*) score (*z*) between Drawings B and A for student *j* across all systems thinking concepts *k* and systems thinking learning levels *l*
$d_{z_{wv}}$	The paired difference in total score (*z*) between Drawings B and A for student *v* in group *w* in the ANOVA for groups test (see description in section **Error! Reference source not found.**)
$d_{z_{w\cdot}}$	The sum of the paired difference in total score (*z*) between Drawings B and A for all students in group *w* in the ANOVA for groups test (see description in section **Error! Reference source not found.**)
$\bar{d}_{z_{w\cdot}}$	The average of the paired difference in total score (*z*) between Drawings B and A for all students in group *w* in the ANOVA for groups test (see description in section **Error! Reference source not found.**)
$d_{z_{\cdot\cdot}}$	The sum of the paired difference in total score (*z*) between Drawings B and A for all students (*v*) in all groups (*w*) in the ANOVA for groups test (see description in section **Error! Reference source not found.**)
Variables Used in Testable Hypotheses	
$\mu_{x_{ik}}$	The mean number (*x*) of systems thinking concept *k* [Elements (E) or Interactions (I) or Roles/Purposes (R)] identified for drawing *i*, for all students, and across all systems thinking learning levels
$\mu_{z_{ik}}$	The mean score (*z*) for systems thinking concept *k* [Elements (E) or Interactions (I) or Roles/Purposes (R)] identified for drawing *i*, for all students, and across all systems thinking learning levels

Variable	Description / Definition
$\mu_{x_{iT}}$	The mean of the total (*T*) number (*x*) of all systems thinking concepts [Elements (E) + Interactions (I) + Roles/Purposes (R)] identified for drawing *i*, for all students, and across all systems thinking learning levels
$\mu_{z_{iT}}$	The mean of the total (*T*) score (*z*) for all systems thinking concepts [Elements (E) + Interactions (I) + Roles/Purposes (R)] identified for drawing *i*, for all students, and across all systems thinking learning levels
$\mu_{d_{x_k}}$	The mean of the paired difference (*d*) between Drawings B and A for the total number (*x*) of systems thinking concept *k* [Elements (E) or Interactions (I) or Roles/Purposes (R)] identified for all students and across all systems thinking learning levels
$\mu_{d_{z_k}}$	The mean of the paired difference (*d*) between Drawings B and A for the total score (*z*) of systems thinking concept *k* [Elements (E) or Interactions (I) or Roles/Purposes (R)] identified for all students and across all systems thinking learning levels
$\mu_{d_{x_T}}$	The mean of the paired difference (*d*) between Drawings B and A for the total number (*x*) of all systems thinking concepts [Elements (E) + Interactions (I) + Roles/Purposes (R)] identified for all students and across all systems thinking learning levels
$\mu_{d_{z_T}}$	The mean of the paired difference (*d*) between Drawings B and A for the total score (*z*) of all systems thinking concepts [Elements (E) + Interactions (I) + Roles/Purposes (R)] identified for all students and across all systems thinking learning levels
$E(d_{x_k})$	The expected value of the paired difference (*d*) between Drawings B and A for the total number (*x*) of systems thinking concept *k* [Elements (E) or Interactions (I) or Roles/Purposes (R)] identified for all students and across all systems thinking learning levels
$E(d_{z_k})$	The expected value of the paired difference (*d*) between Drawings B and A for the total score (*z*) of systems thinking concept *k* [Elements (E) or Interactions (I) or Roles/Purposes (R)] identified for all students and across all systems thinking learning levels
$E(d_{x_T})$	The expected value of the paired difference (*d*) between Drawings B and A for the total number (*x*) of all systems thinking concepts [Elements (E) + Interactions (I) + Roles/Purposes (R)] identified for all students and across all systems thinking learning levels
$E(d_{z_T})$	The expected value of the paired difference (*d*) between Drawings B and A for the total score (*z*) of all systems thinking concepts [Elements (E) + Interactions (I) + Roles/Purposes (R)] identified for all students and across all systems thinking learning levels

Appendix D

10 Appendix D: Research Study Documents

The research study approval notice from the Oregon State University (OSU) Human Research Protection Program (HRPP) and Institutional Review Board (IRB) is presented in section 10.1.

The research study application, or protocol, submitted to and approved by the OSU HRPP and IRB is presented in section 10.2.

The research study consent form approved by the OSU HRPP and IRB is presented in section 10.3.

The research study assent form approved by the OSU HRPP and IRB is presented in section 10.4.

The student worksheet used in the research study and approved by the OSU HRPP and IRB is presented in section 10.5.

The presentation slides used in the research study are presented in section 10.6.

10.1 Research Study Approval Notice

Oregon State University Research Office

Human Research Protection Program
& Institutional Review Board
B308 Kerr Administration Bldg, Corvallis OR 97331
(541) 737-8008
IRB@oregonstate.edu
http://research.oregonstate.edu/irb

Date of Notification	April 19, 2019		
Notification Type	Approval Notice		
Submission Type	Initial Application	Study Number	IRB-2019-0090
Principal Investigator	Javier J Calvo-Amodio		
Study Team Members	Jacobsen, Malaia P; Taylor, Seth H; Well, Jay A		
Study Title	Measuring How Middle and High School Students Learn Systems Thinking		
Review Level	FLEX		
Waiver(s)	Parental Permission		
Risk Level for Adults	Minimal Risk		
Risk Level for Children	Minimal Risk		
Funding Source	None	Cayuse Number	N/A

APPROVAL DATE: 04/19/2019 **EXPIRATION DATE:** 04/18/2024

A new application will be required in order to extend the study beyond this expiration date.

Comments:

The above referenced study was reviewed and approved by the OSU Institutional Review Board (IRB). The IRB has determined that the protocol meets the minimum criteria for approval under the applicable regulations, state laws, and local policies.

This proposal has not been evaluated for scientific merit, except to weigh the risk to the human subjects in relation to potential benefits.

Adding any of the following elements will invalidate the FLEX determination and require the submission of a project revision:

- Increase in risk
- Federal funding or a plan for future federal sponsorship (e.g., proof of concept studies for federal RFPs, pilot studies intended to support a federal grant application, training and program project grants, no-cost extensions)
- Research funded or otherwise regulated by a federal agency that has signed on to the Common Rule, including all agencies within the Department of Health and Human Services
- FDA-regulated research
- NIH-issued or pending Certificate of Confidentiality
- Prisoners or parolees as subjects
- Contractual obligations or restrictions that require the application of the Common Rule or which require annual review by an IRB
- Classified research
- Clinical interventions

Principal Investigator responsibilities:

Oregon State University
Research Office

Human Research Protection Program
& Institutional Review Board
B308 Kerr Administration Bldg, Corvallis OR 97331
(541) 737-8008
IRB@oregonstate.edu
http://research.oregonstate.edu/irb

- Keep study team members informed of the status of the research.
- Any changes to the research must be submitted to the IRB for review and approval prior to implementing the changes. Failure to adhere to the approved protocol can result in study suspension or termination and data stemming from protocol deviations cannot be represented as having IRB approval.
- Report all unanticipated problems involving risks to participants or others within three calendar days.
- Use only valid consent document(s).
- Submit project revisions for review prior to initiating changes.

10.2 Research Study Application (Protocol)

HRPP and IRB Application (Version 1.0)

1.0 General Information

***Please enter the full title of your study:**

Measuring How Middle and High School Students Learn Systems Thinking

***Short Title:**

Measuring Systems Thinking Learning
* This field allows you to enter an abbreviated version of the Study Title to quickly identify this study.

Anticipated study review level:

Flex

2.0 Add Department(s)

2.1 Add the PI's primary department if you do not see it listed below:

Primary Dept?	Department Name
○	**OSU** - 000001 Dept
◉	**OSU** - EMM - Sch Mech/Indust/Manufact Engr

3.0 Study Team

3.1 *Name of Principal Investigator (FAQ: Who can be a Principal Investigator (PI):

Calvo-Amodio, Javier J

3.2 Additional Study Team Members:

Additional investigators:
(Do not list individuals who will receive IRB approval at their own external institution or whose institution has determined that they are not engaged.)

To remove a study team member prior to submitting the application, check the box next to their name and click the "remove" button.

Jacobsen, Malaia P
Student
Taylor, Seth H
Student
Well, Jay A
Staff

Non-Research Support Staff:
(No access to participants, data, or specimens)

To remove a study team member prior to submitting the application, check the box next to their name and click the "remove" button.

3.3 *Please add a Study Contact:

Calvo-Amodio, Javier J
Jacobsen, Malaia P
Taylor, Seth H
Well, Jay A

The Protocol Contact(s) will receive all important system notifications. The Principal Investigator cannot be removed as a study contact, however, additional study contact(s) can be added. All protocol contacts must be listed in 3.2 above.

To remove a study team member from the "protocol contact" section, check the box next to their name and click the "remove" button.

3.4 If required by the PI's department, please select the Designated Department Approval(s):

Add the name of the individual required to approve and sign off on this protocol from your department (e.g. the Department Chair or Dean). Skip if none.

4.0 Help Text

4.1 Do you wish to see the application help text, examples, and links to additional information in this form?

◉ Yes ○ No

5.0 Submission Type

5.1 Select One:

◉ New submission, not previously reviewed or approved by OSU
○ Re-submission of previously approved protocol (expired or migration into iRIS)
○ Request for .118 Determination
○ Convert .118 Determination to a new application

6.0 Study Summary

6.1 Using lay language, briefly describe the study purpose or primary research question:

50 words or fewer. You will be asked for aims, background justification, and specific methods and procedures in later sections.

The purpose of this study is to measure how middle and high school students learn systems thinking using data from a fish tank system drawing activity.

7.0 Determination of Whether the Project Requires IRB Review

7.1 "Research" is defined as a systematic investigation, including research development, testing and evaluation, designed to develop or contribute to generalizable knowledge. Does the project involve research at OSU or elsewhere?

(●) Yes ( ) No

7.2 "Human subject" is defined as obtaining data about, or specimens from, one or more living individuals through intervention, OR interaction, OR the collection of identifiable private information. Does the project involve human subjects at OSU or elsewhere?

(●) Yes ( ) No

7.3 OSU Engagement:

Are any of the following true?

- OSU is the only institution participating in this study
- OSU is the primary awardee on the funding
- OSU employees or students are obtaining consent from participants
- OSU employees or students will have access to individually identifiable data or samples

(●) Yes ( ) No

8.0 Extent of the Review Required by OSU

8.1 Are OSU-affiliated individuals the only people conducting study activities; including recruitment, obtaining consent, data collection, data analysis, data or sample sharing or storage?

(●) Yes ( ) No

9.0 OSU will be the RESPONSIBLE Institution but Review External Documents

9.1 Will OSU be asked to approve this study based on review of documents that have already been approved by another IRB?

( ) Yes (●) No

10.0 Regulatory Flexibility

10.1 Instructions:

The requirement to comply with some regulations and policies can be waived for eligible studies. Your answers to the questions in this section will assist us in determining whether this study is eligible for a flexible application of the regulations.

If "no" to all of the questions in this section, the study may be eligible for "flex" review. Flex studies will not be assigned an exempt or expedited category. When applicable, subsequent sections will contain special instructions related to these studies.

If "yes" to one or more of the questions in this section, regulatory flexibility cannot be applied to this project and the study will be reviewed using an exempt, expedited, or full board process.

Information about Regulatory Flexibility

10.2 Does the study involve more than minimal risk to participants?

○ Yes ◉ No

10.3 Will any of the participants be prisoners or parolees? This refers to the target population, not incidental enrollment.

○ Yes ◉ No

Information about research with prisoners

10.4 Does the study involve federally classified research procedures and/or results that are legally knowable only by individuals with US government security clearance?

○ Yes ◉ No

10.5 Does the study include any clinical interventions?

○ Yes ◉ No

Note: For the purposes of OSU policy, **clinical intervention** is defined as one that is intended to change or assess a health-related processes and/or endpoint. Examples include the use of drugs, dietary supplements, devices, blood draws, imaging (e.g., DXA, x-ray), delivery systems (e.g., telemedicine, face-to-face), diet, cognitive therapy, exercise, and any intervention that includes treatment, prevention, or diagnostic strategies.

10.6 Is there federal funding or a plan for future federal sponsorship for this study?

○ Yes ◉ No

Note: Research funded or otherwise regulated by a **federal agency that has signed on to the Common Rule**, including all agencies within the Department of Health and Human Services. Included are proof of concept studies for federal RFPs, pilot studies intended to support a federal grant application, training and program project grants, no-cost extensions.

10.7 Are there contractual obligations or restrictions triggered by a non-federal award that require the application of the federal regulations or which require that annual review be conducted by an IRB?

○ Yes ◉ No

10.8 Is there an NIH-issued or pending Certificate of Confidentiality?

○ Yes ◉ No

Note: Certificates of Confidentiality protect the privacy of research subjects by prohibiting disclosure of identifiable research information to anyone not connected to the research except when the subject consents or in a few other specific situations. NIH-funded researchers are automatically issued a Certificate through their award if the information collected could be individually identifiable or "*for which there is at least a very small risk, that some combination of the information, a request for the information, and other available data sources could be used to deduce the identity of an individual.*"

10.9 Does this study need to be registered with ClinicalTrials.gov?

○ Yes ◉ No

Information about ClinicalTrials.gov Registration & Reporting Requirements

10.10 Does the study involve any FDA-regulated components?

○ Yes ◉ No

11.0 Conflicts of Interest and Competing Relationships

11.1 Does a researcher or family member have a financial or other business interest in an entity that is supplying funding, materials, products, equipment, research participants, or the site of data collection for the current research project?

◉ Yes ○ No

Provide details:

Mr. Jay Well works full time for the Science and Math Investigative Learning Experiences (SMILE) Program at Oregon State University, and he is also a study team member. This study is not funded by the SMILE Program and it is not evaluating the effectiveness of the SMILE Program or of Mr. Well, therefore no financial conflicts of interest are present. However, the SMILE Program will be providing study participants who may have a pre-existing relationship with Mr. Well. The existence of any such relationship will have no affect upon the participants in this study.

12.0 Sources of Funding and Support for this Project

12.1 Is funding for the project pending/awarded?

○ Yes (Internal or External)
◉ No (Unfunded)

12.6 Is an external (non-OSU) organization or company providing material, equipment, drugs, supplements, or devices for this study?

○ Yes ◉ No

13.0 Study Overview

13.1 List the study aims or research questions and a general description of the participant population:

The primary aim of this study is to understand how middle and high school students learn systems thinking. The specific research questions are as follows:

1. Can systems thinking learning be measured for middle and high school students?
2. Can systems thinking learning be measured using a fish tank system drawing activity?

The participant population for this study is split into two groups of students participating in an activity organized by the Science and Math Investigative Learning Experiences (SMILE) Program. The first group is middle school students and the second group is high school students. Both groups are mixed in age and school of origin, but all students are from Oregon and participate in activities related to OSU's SMILE Program. The middle school students range in age from 11 - 14 years old and the high school students range in age from 14 - 18 years old.

Provide survey questions, questionnaires, interview and focus group guides, references/citations, etc., as separate attachments. Attachments are uploaded in a single section at the end of this form.

13.2 Provide details of where data will be collected:

Data will collected at the OSU Corvallis campus.

13.3 Provide background justification:

Background justification should support the objectives of the research as well as the knowledge that is anticipated from the research results. Explain the need for the study and what gap in knowledge the results are expected to fill. Summarize relevant existing data, literature, past and ongoing studies, and how your study ties in with these.

Provide specific methods and procedures in a later section.

- The knowledge that is anticipated from the research results are a quantitative method for measuring a student's current state of learning systems thinking using the fish tank activity as the measurement tool. Based on the research results, the measurement tool could be proposed as a tool to measure systems thinking learning for other populations.
- This study is needed because we need to understand how students learn systems thinking. Systems thinking is not currently taught as part of formal education, and as a subject it differs from other commonly taught subjects.
- Therefore, to design lessons around systems thinking concepts we need to understand the current state of systems thinking learning that students possess.

13.4 Does the study involve any of the following?

Check all that apply:

- ☐ Education Records: Does the study involve the use of student education records?
- ☐ Food or Beverage: Does the study involve providing participants with commercially purchased food intended as a courtesy or compensation?
- ☐ Does the study involve participants ingesting, tasting, or smelling a food, a beverages, or a component thereof for the purpose of research?
- ☐ Drugs or Biologics: Are one or more drugs or biologics being studied as part of this project?
- ☐ Dietary Supplements: Are one or more dietary supplements being studied as part of this project?
- ☐ Devices: Are one or more medical devices being studied as part of this project?
- ☐ Radiation: Does the study involve exposing participants to radiation?
- ☐ Biological Samples: Does the study involve the collection or receipt of biological samples?
- ☐ Limited to chart review or analysis of large, pre-existing datasets.
- ☑ None of the above

14.0 Target Enrollment

14.1 What is the target enrollment number?

300

☐ N/A

14.2 Provide scientific justification for the target enrollment number:

The target enrollment number is 300 for three reasons.

1. First, this enrollment number approximates the number of students that typically visit the OSU campus for a yearly SMILE event each Spring.
2. Second, approximately half of the participant enrollments (about 150) will be middle school students and the other half will be high school students. The data collected from each group will provide insight on differences between the two groups of students in regards to learning systems thinking.

3. Third, sample sizes of 150 students for each group will provide sufficient statisitical significance to achieve the study aims and answer the research questions. This is calculated for a 95% confidence level, out of approximately 553,000 students enrolled in the state of Oregon, with a confidence interval of +/- 6%.

15.0 Participant Demographics

15.1 Instructions:

Justification must be provided for excluded populations. Excluding certain categories of people may reduce generalizability. For example: Study results may not be applicable to the general population of adults in the US if pregnant women, people who do not speak English, and Native Americans are excluded which may, in turn, reduce the scientific benefit of the overall study.

The IRB will not approve a study that fails to provide adequate scientific and ethical justification for excluding persons who might directly benefit from the research, nor will the IRB approve a study that fails to provide scientific and ethical justification for targeting a category of participants who are vulnerable to coercion or undue influence.

15.2 Age ranges:

Check all that apply:

- ☐ 0-7
- ☑ 8-17
- ☑ 18-89
- ☐ 90+

Provide scientific justification for limiting enrollment to this age range:

This study aims to learn how middle and high school students learn systems thinking, therefore the population age must be within the range of 11 to 18 years old.

15.3 Will people from any of the following populations be permitted to enroll?

- ☐ Pregnant women AND the study involves more than minimal risk OR a physical intervention
- ☑ Children

Guidance on research with children.

Note: All study team members conducting research with unaccompanied children must contact Human Resources to confirm their eligibility before they will be permitted by OSU to have these minors in their care or custody. For the purposes of this application, "unaccompanied" means any research activities with children in the absence of their parent(s) or legal guardian(s).

- ☐ People in the European Union or the European Economic Area (EEA) (regardless of citizenship)

15.4 Will you intentionally recruit and enroll from any of the following populations?

- ☑ Economically or educationally disadvantaged persons
- ☐ Adults lacking capacity to consent
- ☐ American Indians or Alaska Natives
- ☐ Prisoners
- ☐ Children in foster care or wards of the state

15.5 Will any of the following OSU-affiliated groups be permitted to enroll?

Check all that apply:

- ☐ Students
- ☐ Students currently enrolled in a class or lab instructed by a study team member
- ☐ Employees
- ☐ Employees who report to or are otherwise supervised by a study team member
- ☐ Any of the study team members

15.6 Will people who do not speak or read English be permitted to enroll?

○ Yes ◉ No

Does the target population include non-English speakers?

◉ Yes ○ No

Is the study specifically about people who speak English fluently (example: Study of English teachers' experience with an experimental curriculum)?

○ Yes ◉ No

Provide justification for the exclusion. Please also explain whether and how the resulting data can be generalized or applied to people who do not speak English if they did not participate in the study:

We do not anticipate any non-English speaking students to participate in this study. However, parents of children who will participating in the SMILE activity may not speak English. Since we are asking for parental consent, we plan to ask SMILE teachers and staff to notify the study team if a parent needs the consent (parental permission) document provided to them in another language. In this case, we will work with a translator to write a consent form in the desired language and submit the form to IRB for approval before continuing with the consent process.

15.7 Are people of any sex, gender/gender identity eligible to participate?

◉ Yes ○ No

15.8 Are people of any race or ethnicity eligible to participate?

◉ Yes ○ No

15.9 List any inclusion criteria not addressed above and explain why this is a scientifically appropriate population for the study:

Criteria:	Explain (if not obvious):
No records have been added	

15.10 List any exclusion criteria not addressed above and the reason for the exclusion:

Criteria:	Explain:
Current middle or high school student participating in SMILE Program activities	This study seeks to understand how middle and high school students that participate in SMILE activities are learning systems thinking.

16.0 Identification and Recruitment of Participants

16.1 How will potential participants be identified and recruited?

Potential participants will be identified and recruited by the SMILE Program. The participants have been selected to attend a pre-existing event hosted by SMILE on the OSU campus in late April 2019. The participants will be participating in a systems thinking activity regardless of whether thier data from that activity is used for research.

16.2 The recruitment materials should include the following information: a) Study title b) Name of the Principal Investigator c) A clear statement that this is research d) Contact information for study personnel.

If you will not include one or more of the above elements, provide justification for the omission:

Attach advertisement or other recruitment material (including content of electronic posts or email). Attachments are uploaded in a single section at the end of this form.

17.0 Informed Consent

17.1 Consent Process:

Required elements of consent

Will consent be sought from participants?

- (●) All of the participants: Consent will be sought from each participant and all of the basic elements of consent will be presented to subjects
- ( ) Some of the participants: Seeking a waiver of consent, or of one or more of the elements of consent, for some participants
- ( ) None of the participants: Seeking a waiver of consent, or of one or more of the elements of consent, for all participants

Indicate where and when consent will be obtained (e.g., in a location that protects the participants' privacy, prior to involvement in any study activities):

Since this research study involves children, we will obtain consent using a parental permission form. This form will be included in the permission slip package sent home with each student who has been invited by the SMILE Program to visit the OSU campus on April 27, 2019 for the SMILE Middle School Challenge or on April 26, 2019 for the SMILE High School Challenge. This form will notify parents of the research study and include all of the basic elements of consent with a one-week opt-out period. If a parent wishes to opt out of their child's participation in this study, they can contact the Principal Investigator or return the signed consent form to the SMILE Program. Consent will only be sought from one parent or legal guardian for each child in order to opt out of this research study.

Explain how comprehension of consent information will be assessed and what questions will be asked of the participants to determine comprehension of the study information:

Examples: What questions can I answer for you? To ensure that you understand what the study involves, would you please tell me what you think we are asking you to do? In your own words, can you tell me what the biggest risk to you might be if you enroll in this study?

Consent information will not be assessed on the parental permission form, but parents will be able to contact the Principal Investigator to ask any questions about the study.

Will consent be obtained in a web-based environment?

( ) Yes (●) No

Will all participants sign consent documents?

( ) Yes (●) No

17.3 Request a waiver of the requirement to obtain signatures on consent documents:

You are seeing this section because you indicated above that some or all of the participants will not be asked to sign consent documents. If this process will vary across cohorts, phases, or activities, add one entry for each.

Entry 1

Participant Group or Activity Name:	All participants **For example:** Group 1 – Teachers; Group 2 – Parents of children being interviewed; OR Phase 1 participants; Phase 2 participants; OR All participants
Will this participant group be asked to sign and date written consent forms?	There is no IRB-related requirement for signed consent forms if the study is exempt or eligible for regulatory flexibility. However, other laws or regulations, such as FERPA, may require that a signature be obtained. ○ Yes ◉ No
If not, which of the criteria below does this study meet?	**Check all that apply:** ☐ The only record linking the subject and the research would be the informed consent form and the principal risk would be potential harm resulting from a breach of confidentiality. Each subject (or legally authorized individual) will be asked whether the subject wants documentation linking the subject with the research, and the subject's wishes will govern; ☑ The research presents no more than minimal risk of harm to subjects and involves no procedures for which written consent is normally required outside of the research context; or ☑ Study is exempt or eligible for a flexible application of the regulations. ☐ Written consent will be obtained for the primary research activities but not for eligibility screening.
Will participants be provided with a copy of their consent form?	◉ Yes ○ No **Federal regulations require that a written copy be given to the person signing the consent form. If you will not provide a copy to participants, please explain why this requirement cannot be met:**

17.4 Parental Permission:

Will parental permission be obtained before children are enrolled?

◉ Yes ○ No

If children may be enrolled in the research, provide a plan for obtaining consent from parents or legal guardians:

Consent from parents or legal guardians will be obtained using a parental permission form. This form will be included in the permission slip package sent home with each student (child) who has been invited by the SMILE Program to visit the OSU campus on April 27, 2019 for the SMILE Middle School Challenge or on April 26, 2019 for the SMILE High School Challenge. This form will notify parents of the research study and include all of the basic elements of consent with a one-week opt-out period. If a parent wishes to opt out of their child's participation in this study, they can contact the Principal Investigator or return the signed consent form to the SMILE Program. Consent will only be sought from one parent or legal guardian for each child in order to opt out of this research study.

18.0	Assent

18.1

18.2 Assent Process

Provide information about the assent process below. If the assent process will vary across cohorts, phases, or activities, add one entry for each.

Entry 1

Participant group name:	All participants
Are you seeking a waiver of the requirement to obtain assent for this participant group?	○ Yes ◉ No **If Yes, check the appropriate reasons below:** ☐ The ages, maturity, or psychological state of the individuals to be enrolled make them incapable of providing assent; or ☐ The intervention or procedure involved in the research holds out a prospect of direct benefit that is important to the health or well-being of the participants and is available only in the context of the research; or ☐ The research involves no more than minimal risk, and the research could not practicably be carried out without the waiver of assent.
If no, provide a description of the assent process for this participant group:	Assent will be obtained from all participants (students) prior to the research study activity. Students will be provided with a written assent form that includes the same elements on the parental permission (consent) form. Students will have the opportunity to ask questions about the study before deciding whether to provide assent. All of the students will participate in the systems thinking activity regardless of whether they provide assent to use their data in the research study. All of the students will write their name on the assent form so that we can remove those students from data collection whose parents opted them out of the study. If a student decides not to participate in the study, they will sign the bottom section of the assent form to indicate that they do not want to participate and we will not collect data from them.
Indicate who will discuss the study with the participant and, if not the parent or legally authorized representative, describe their training in presenting information to the target population:	One of the study team members will discuss the study with the participants (students) and present study information. All study team members have previous experience working with students in the SMILE Program and with conducting research studies.
Will a written assent document or explanation of research be provided to participants?	◉ Yes ○ No
If yes, will a written signature be obtained from participants prior to enrollment?	◉ Yes ○ No
If no, will the assent process be strictly verbal (no written document)?	○ Yes ◉ No

Relevant attachments may include:

- Written assent documents
- Verbal assent guides

Attachments are uploaded in a single section at the end of this form.

19.0 Eligibility Screening

19.1 Will participants be screened for eligibility?

○ Yes ◉ No

20.0 Methods and Procedures

20.1 Provide a description of the methods and procedures to be followed during this research project:

- If the study involves accessing student education records, list all data to be used (e.g. course grades, assignments, GPA, video-recordings of class activities, etc.)
- Identify any surveys or questionnaires that are being tested or validated instruments that have been modified for the purposes of this study
- Identify any novel or modified experimental activities that are being tested the purposes of this study.
- Specific information related to the use of drugs, devices, biologics, food, biospecimens, and radiation will be requested later in this document.

The fish tank system activity is the systems thinking measurement tool that has been modified for the purpose of this study. The following is the procedure that will be followed during this research study:

1. **Informed Consent**
   - Send informed consent (parental permission) form home with students in early April 2019 who have been invited by the SMILE Program to attend the SMILE Middle School Challenge or the SMILE High School Challenge.
   - Collect the forms that opt a student out of the research study (to be used later in step 4).
2. **High School Challenge on April 26, 2019**
   - Review the research assent form with students.
   - Ask them to write their name on the form.
   - Ask them to sign and date the assent form if they do not want to participate in the research study.
   - Facilitate the background questions (PART A):
     - Ask students to answer Question 1: What is your familiarity with fish tanks? (students will circle the response that best represents their familiarity with fish tanks).
     - Ask students to answer Question 2: Have you participated in this activity before? (students will circle either YES or NO)
   - Facilitate the fish tank system activity (PART B):
     - Ask students to draw and label any elements in the fish tank system
     - Ask students to draw and label any interactions in the fish tank system
     - Ask students to draw and label the roles of each element and interaction in the fish tank system
3. **Middle School Challenge on April 27, 2019**
   - Review the research assent form with students.
   - Ask them to write their name on the form.
   - Ask them to sign and date the assent form if they do not want to participate in the research study.
   - Facilitate the background questions (PART A)
     - Ask students to answer Question 1: What is your familiarity with fish tanks? (students will circle the response that best represents their familiarity with fish tanks).
     - Ask students to answer Question 2: Have you participated in this activity before? (students will circle either YES or NO)
   - Facilitate the fish tank system activity (PART B)
     - Ask students to draw and label any elements in the fish tank system

- Ask students to draw and label any interactions in the fish tank system
- Ask students to draw and label the roles of each element and interaction in the fish tank system

4. **Data Collection & Sorting (at the end of each session)**
   - Collect each student's assent form and data (fish tank) activity sheet.
   - Remove and destroy data from students whose parents have opted them out of the research study (parental permission / consent form).
   - Remove and destroy data from students who did not provide assent (opted out) for participating in the research study.
   - Separate the parental permission / consent forms, assent forms, and data activity (fish tank) sheets for all students who do provide consent and assent to participate in the research study.
   - Create digital copies of parental permission / consent forms, assent forms, and data activity sheets and store copies on secure cloud-based server.
   - Destroy physical copies of consent and assent forms.

20.2 If any of the activities would be conducted regardless of the research, briefly describe those activities here:

Participants (students) will be attending either the SMILE Middle School Challenge or SMILE High School Challenge and will be participating in a systems thinking activity as part of these events. This systems thinking activity will ask students to draw and label elements, interactions, and roles of elements in a fish tank system. After students have completed their drawing, the activity will transition to introducing and discussing core systems thinking concepts (elements, relationships, perspectives, etc.) that we want the students to learn, using the fish tank system drawing as an example. We are asking for consent to use this drawing as data for the research study.

20.3 Will participants be audio or video recorded?

○ Yes ◉ No

20.4 Does the study involve conducting research activities online?

○ Yes ◉ No

20.5 Is the study designed to be implemented in phases, where fully describing one phase is dependent upon the outcome of another?

○ Yes ◉ No

20.6 Describe each study team members' role on the project and their qualifications to safely and appropriately to conduct these activities (e.g., related academic degree(s), previous professional experience in a relevant area, applicable certification, specialized skills):

Javier Calvo-Amodio is the Principal Investigator for this research study. Javier's role on the study team is to oversee all study activities and be in charge of securely storing all study data.

Jay Well works for the SMILE Program at Oregon State University. Jay has been involved in many resesarch studies overseen by SMILE and has extensive experience working with children. Jay's role on the project team will be to organize the informed consent process to gain parental permission and to facilitate the assent process for students on the day of the study activity.

Seth Taylor is a graduate student researcher at Oregon State University. Seth's role on the study team is to create and maintain all IRB-related documentation and help facilitate the study activity.

Malaia Jacobsen is a graduate student researcher (starting on Spring 2019) at Oregon State University. Malaia's role on the study team is to help facilitate the study activity.

21.0 Compensation

21.1 Describe any compensation or incentives for participants:

No compensation will be provided to participants in this study.

22.0 Costs

22.1 Describe any costs to participants that are associated with the study (e.g., parking, travel, etc.):

There are no additional costs to participants in this study because the participants will participate in the activity regardless of whether they choose to be a part of the research study.

23.0 Privacy and Confidentiality

23.1 Instructions:

Many of the terms used in this section are defined in the **glossary** under the heading "Privacy, Confidentiality, and Identifiers".

23.2 Privacy, in the context of a research protocol, means respecting an individual's right to be free from unauthorized or unreasonable intrusion, including control over the extent, timing, and circumstances of obtaining personal information from or about them. Explain how privacy will be respected when identifying and recruiting potential participants:

Potential participants will be receiving a permission slip to attend the event hosted by SMILE regardless of whether we conduct this study which maintains privacy during the recruitment process.

Privacy will be maintained after recruitment by removing all identifiers from the collected materials. The identifiers will be destroyed.

23.3 Check all that apply:

- [x] Direct and/or indirect identifiers will be requested or recorded
- [ ] Data will be collected anonymously or provided to researchers without identifiers
- [ ] Researchers will know the identity of participants but will not record identifying information
- [ ] Other

23.5 List the direct identifiers (e.g., names, social security numbers, addresses, telephone numbers, student ID, medical record number, mTurk ID, photographs, video recording):

Names

23.6 Indicate whether identifiers or codes will be retained that could link the identity of the participant to the sample:

The names of students in the study will only be collected on consent and assent forms. Students will not write their name on the fish tank activity sheet (data) which will be detached from the assent form by the researchers upon completion of the activity. Samples, consent forms, and assent forms will be retained separately so that the samples cannot be traced to a specific participant.

23.7 List the indirect identifiers (e.g., combination of demographic and other variables such as gender, race, ethnicity, age, zip code, company affiliation, class standing, department, audio recording):

- Generalized class standing (middle school or high school)
- Age range (11 to 18 years old)

23.8 Describe the steps that will be taken to minimize the chances of a breach of confidentiality during and after data collection (e.g., coding system, pseudonyms, etc.):

The chance for a breach of confidentiality will be minimized as follows:

- **During data collection...**
  - Only the researchers and those affiliated with the SMILE Program will be present.
- **After data collection...**
  - Immediately after data (fish tank activity sheets) are collected they will be sorted into two groups based on the consent forms - one group for consenting and one group for non-consenting.
  - For each data sample in the non-consenting group, the assent form will be detached and stored separately from the samples.
  - For each data sample in the consenting group, two more groups will be formed - one group for assenting and one group for non-assenting.
  - For each data sample in both groups (assenting and non-assenting), the assent form will be detached and stored separately from the samples.
  - Consent and assent forms will be scanned to create electronic copies and the physical copies will be destroyed.

23.9 Will a copy of the consent form, test results, or other research study information be placed in the participants' record (e.g., medical, personnel, or education record)?

○ Yes ◉ No

24.0 Record Retention

24.1 Will the Principal Investigator store research records in a secure and audit accessible manner for a minimum of three years post-study termination?

◉ Yes ○ No

24.2 Will the student researcher <u>also</u> store research records after the study has closed?

○ Yes
◉ No
○ N/A

24.3 If the study is FDA-regulated, confirm the PI will also comply with the following relevant records retention requirements:

In accordance with **21 CFR 312 (drugs),** an investigator or sponsor shall retain the records and reports for 2 years after a marketing application is approved for the drug; or, if an application is not approved for the drug, until 2 years after shipment and delivery of the drug for investigational use is discontinued and FDA has been so notified:

○ Yes
◉ N/A

Comments:

In accordance with **21 CFR 812 (devices)**, an investigator or sponsor shall maintain the records required by this subpart during the investigation and for a period of 2 years after the latter of the following two dates: The date on which the investigation is terminated or completed, or the date that the records are no longer required for purposes of supporting a premarket approval application or a notice of completion of a product development protocol:

- ○ Yes
- ○ No
- ◉ N/A

Comments:

24.4 Will a link between study code numbers and direct identifiers be retained after data collection is complete?

○ Yes ◉ No

24.5 If audio and/or video recording, indicate whether these files will be destroyed after transcripts and /or coding is verified. If A/V files will be retained, provide justification for retention:

N/A

24.6 Will data be stored for future studies?

◉ Yes ○ No

Indicate how long data will be retained, how it will be stored, and what it will be used for:

Data will be retained by the PI indefinitely. Data will be stored on a secure, cloud-based server controlled by the PI. The data will be used as a basis for future studies and to provide insight on creating future systems thinking lessons for the SMILE Program or other educational institutions.

The information in the consent form should convey the area of study for future projects. Explain whether and how participant permission will be sought for future studies of existing data:

Participant permission will not be sought for future studies of existing data because the data collected will be non-identified immediately after data collection is complete.

Indicate whether participants will be contacted by researchers in the future for the purpose of updating information:

Participants will not be contacted by researchers in the future for the purpose of updating information.

Indicate whether and how participants can opt out of any sharing or future use of their data:

Participants will not be able to opt out of future use of their data.

25.0 Sharing Data and Biological Samples

25.1 Will data and/or samples be shared with individuals or entities external to OSU (e.g., made public, shared with sponsor, sent to collaborators, given to people at the site of research, etc.)?

○ Yes ◉ No

26.0 Publication

26.1 Could any of the participants be identifiable in publication or presentation (e.g., results will be reported using direct quotes, group or tribe name, company name and position title)?

○ Yes ◉ No

26.2 Is the study student-driven (for the purpose of a thesis, dissertation, or other)?

◉ Yes ○ No

26.3 Will manuscripts, presentation materials, theses, or dissertations be stored in Scholars Archive?

◉ Yes ○ No

26.4 Will individually identifiable data or specimens be stored in an archive or repository?

○ Yes ◉ No

27.0 Data Security

27.1 What is the data security level for this study?

Level 1

Use this matrix to determine the data security level and related requirements for this study.		Breach of confidentiality p	
		No Risk	Minimal Risk
Are data and/or subjects:	De-Identified or anonymous?	**Level 1**	**Level 1**
	Identifiable or coded?	**Level 1**	**Level 2**

27.2 Data Security Level 1:

Will the following security requirements be met:

- Information will be shared and stored in a manner that provides access only to authorized individuals.
- If information is stored on a computer, the system will have fully patched operating systems and applications, and current virus definitions. Information may be stored in cloud-based servers.

◉ Yes ○ No

Will the following security recommendation be met?

- A plan for routine back-ups of all data will be in place

◉ Yes ○ No

Outline any additional safeguards that will be taken:

Data will be stored on a secure, cloud-based server by the Principal Investigator. Separate files will be stored for assent fo samples with no way to trace assent or consent forms to the samples.

28.0 Potential Reporting Obligations

28.1 Study includes collection of information regarding child abuse or neglect OR it is reasonable to expect that child abuse or neglect could be observed or revealed to the researchers?

○ Yes ◉ No

28.2 Study includes collection of information regarding sexual harassment or sexual violence OR it is reasonable to expect that such information could be revealed to the researchers?

○ Yes ◉ No

28.3 Study includes collection of information regarding harm to self or others OR it is reasonable to expect that such information could be observed or revealed to the researchers?

○ Yes ◉ No

29.0 Certificate of Confidentiality

29.1 A Certificate of Confidentiality has been automatically deemed issued because this study is NIH-funded and includes individually identifiable data?

○ Yes
◉ No
○ N/A

29.2 A Certificate of Confidentiality from the NIH has been obtained or will be sought for this study because it includes the collection of individually identifiable, "sensitive" data?

○ Yes
◉ No
○ N/A

30.0 Risks

30.1 If children will be enrolled, which of the following four federal categories applies:

Check one:

◉ Research does not involve greater than minimal risk to children.
○ Research involves more than minimal risk to children but the study holds prospect of direct benefit to the participants.
○ Research involves more than minimal risk to children and there is no prospect of direct benefit to participants, but the study likely to yield generalizable knowledge about the participants' disorder or condition.
○ Research is not otherwise approvable under the federal regulations but the study presents an opportunity to understand, prevent, or alleviate a serious problem affecting the health or welfare of the participants.

30.2 Describe all reasonably foreseeable risks to study participants:

We do not foresee any risks to study participants beyond the inherent risks associated with everyday educational activities.

30.3 Describe all steps taken to minimize risks:

Participation in the systems thinking activity (that will occur regardless of participation in the research study) is voluntary and students may choose to not participate at any time. Participation in the research study is voluntary and students may choose to not participate at any time.

31.0 Benefits

31.1 Describe potential benefits to the individual participants, to society, and to science:

- **The potential benefit to the individual participant**s in this study is improved educational lessons on systems thinking concepts. Students will directly benefit from lessons that are designed with greater insight on how students learn systems thinking.
- **The potential benefit to society** is the increase in the number of people who are systems thinkers and can leverage this skill to solve the complex problems facing society.
- **The potential benefits to science** are: 1) The increase in knowledge about how students learn the topic of systems thinking and 2) The validation of a tool (activity) that can be used to measure systems thinking learning.

32.0 Training and Oversight

32.1 Is the PI the only member of the study team?

○ Yes ◉ No

32.2 Describe the plan for confirming or providing training related specifically to the study activities and for supervising all study team members:

The PI will confirm that all study team members have current research training through the CITI Program, and if not they will need to complete this training before being added to the study team. At a minimum the Human Subjects - Group 1. Social / Behavioral training must be completed by each study team member. No additional training is required for the study activities.

32.3 Describe the plan for training related specifically to obtaining informed consent and maintaining confidentiality:

The PI will provide training related specifically to obtaining informed consent and maintaining confidentiality and will oversee adherence of these two study components.

32.4 Explain how oversight of study team members will be handled during PI absences (sabbaticals, non-contract months, etc.):

The PI does not plan to be on sabbatical. Non-contract months do not apply for the PI.

33.0 Application Questions Complete

33.1 Having completed the application questions, please return to section 1.0 to confirm that you have selected the appropriate review level, then return to this section to complete the application.

33.2 Click the box below to close all help text notes (required):

If the application is complete and ready to be submitted, please click "Close Help Text, Examples, Links". If you are revising the application in response to submission corrections or review response, you can click "Re-open Help Notes" to make all help notes visible again.

◉ Close Help Text, Examples, Links
○ Re-open Help Text, Examples, Links

33.3 Please click Save & Continue to proceed to the Initial Review Submission Packet.

The Initial Review Submission Packet is a short form filled out after this application has been completed. This is where you will attach documents.

10.3 Research Study Consent Form

Oregon State University

RESEARCH STUDY CONSENT FORM

Study Title:	Measuring How Middle and High School Students Learn Systems Thinking
Principal Investigator:	Javier Calvo-Amodio
Study Team:	Jay Well, Seth Taylor, & Malaia Jacobsen
Version:	V1.1-04182019

Purpose: We are asking for your consent to use your child's results from a systems thinking activity in a research study being conducted by Oregon State University (OSU) researchers. The purpose of this study is to understand how middle and high school students are learning systems thinking. Systems thinking is a way of seeing the world and solving problems using systems. We plan to measure the current state of systems thinking learning among middle and high school students by using the results from a systems thinking activity about fish tanks.

We are asking to use your child's activity results in this research study for two reasons. First, your child is currently in middle or high school. Second, your child is attending the Middle School Challenge on April 27, 2019 or the High School Challenge on April 26, 2019 on the OSU campus in Corvallis, OR hosted by the Science and Math Investigative Learning Experiences (SMILE) Program.

Your child should not participate in this study if they are not currently in middle or high school, or if they are not attending the SMILE Middle School Challenge on April 27, 2019 or the SMILE High School Challenge on April 26, 2019 on the OSU Corvallis campus.

Activity: Your child will be participating in a systems thinking activity during the SMILE Challenge events. During this activity, your child will draw and label elements and interactions they think are present in a fish tank system in order to learn about systems thinking concepts. We are asking for your consent to include your child's fish tank system drawing in this research study. If you or your child decides not to include the drawing in this study, your child will still participate in the activity and we will collect their drawing, but we will not include their drawing in this study.

Risks: There are no additional risks for your child if they participate in this research study. Your child will not be graded or evaluated by the researchers or by the SMILE Program. Your decision to include, or not include, your child's fish tank system drawing in this study will not affect your child's relationship with the researchers, your child's relationship with OSU's SMILE Program, or your child's ability to participate in SMILE-related events.

Benefits: Neither you nor your child will receive any direct benefits, payments or other incentives for participating in this research study. However, the results of this study might be used to create future systems thinking lessons that you or your child may use.

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Oregon State University

Confidentiality: Your child will submit their fish tank system drawing after the systems thinking activity regardless of whether you or your child decides to include the drawing in this research study. Your child will write their name on the drawing, but their name will only be seen by the researchers. Other children participating in this activity may find out that your child participated in this study. We will write a report when the study is over, but we will not use your child's name in the report.

We would like to ask for your permission now to use your child's fish tank system drawing without having to ask you again in the future. We will only use your child's drawing in other studies about systems thinking learning and creating systems thinking lessons. We will remove your child's name from their drawing before we use it for future studies.

Voluntary: The decision to include your child's fish tank system drawing in this research study is voluntary. You can decide to include, or not include, your child's drawing in this study at any time by either contacting the Principal Investigator, Javier Calvo-Amodio, by email (Javier.Calvo@oregonstate.edu) or by phone ((541) 737-0696), or by returning the completed bottom part of this form to the SMILE Program within one (1) week. Otherwise, we will assume that you consent to let us include your child's fish tank system drawing in this study given that there are minimal risks.

Study Contacts: If you have any questions or if there is anything that you do not understand about this research study, please contact Javier Calvo-Amodio by phone ((541) 737-0696) or by email (Javier.Calvo@oregonstate.edu). You can also contact the Human Research Protection Program with any concerns that you have about your rights or welfare as a study participant. This office can be reached by phone: (541) 737-8008 or by email: IRB@oregonstate.edu

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I, ____, *[Write your first and last name]*

do not want the drawing from my child, ____,
[Write your child's first and last name]

included in the research study titled: "Measuring How Middle and High School Students Learn Systems Thinking" held during the SMILE Middle School Challenge on April 27, 2019 or the SMILE High School Challenge on April 26, 2019 at the Oregon State University campus in Corvallis, OR.

______________________________ ______________________________
Signature Date

OSU HRPP and IRB
IRB NUMBER: IRB-2019-0090
IRB APPROVAL DATE: 04/19/2019
IRB EXPIRATION DATE: 04/18/2024

10.4 Research Study Assent Form

Oregon State University

RESEARCH STUDY ASSENT FORM

Study Title:	Measuring How Middle and High School Students Learn Systems Thinking
Principal Investigator:	Javier Calvo-Amodio
Study Team:	Jay Well, Seth Taylor, & Malaia Jacobsen
Version:	V1.1-04182019

We are inviting you to take part in a research study. You do not have to be in the study if you do not want to. You can also decide to be in the study now and change your mind later.

We would like you to ask us questions if there is anything about the study that you do not understand. After all of your questions have been answered, you can decide if you want to be in the study or not.

This research study is about how students learn systems thinking. Systems thinking is a way of seeing the world and solving problems. The results of this study will be used to create new systems thinking lessons for students like you, and to understand how you are learning systems thinking in order to make existing lessons better.

We are asking you if you want to be in this research study because you will be participating in a systems thinking activity during the SMILE Middle School or SMILE High School Challenge. During this activity, you will draw and label elements and interactions that you think are present in a fish tank system in order to learn about systems thinking concepts.

If you take part in this research study, we will ask for your permission to include your fish tank system drawing in our study. If you decide not to include your drawing in this study, you will still participate in the activity and we will collect your drawing, but we will not use it for the study.

Your decision to include, or not include, your drawing in this research study will not affect your relationship with the researchers, your relationship with OSU's SMILE Program, or your ability to participate in SMILE-related events.

Other people participating in the SMILE Challenge events may find out that you participated in this research study. We will write a report when the study is over, but we will not use your name in the report. We would like to ask for your permission now to use your fish tank system drawing without having to ask you again in the future. We will only use your drawing in other studies about systems thinking learning and creating systems thinking lessons. We will remove your name from your drawing before we use it for future studies.

Oregon State University

If you decide not to include your fish tank system drawing in this research study, you must complete the bottom part of this form by providing your signature and the date.

If you do not complete the bottom part of this form, we will assume that it is okay to include your fish tank system drawing in this research study.

Please write your name here: ____

***Provide your signature and the date below if you decide not to include your fish tank system drawing in this research study.*

Your Signature: ____

Date: ______________________________________

OSU HRPP and IRB
IRB NUMBER: IRB-2019-0090
IRB APPROVAL DATE: 04/19/2019
IRB EXPIRATION DATE: 04/18/2024

10.5 Research Study Student Worksheet

Note: The warm-up activity (Drawing A) was administered on page 3 of the worksheet which was a blank sheet of paper (not shown here). Page 4 was intentionally left blank.

SMILE Middle and High School Challenge – April 26-27, 2019
Systems Thinking Activity

PART A

Question 1:
What is your familiarity with fish tanks? Circle the number corresponding to the phrase that best represents your familiarity with fish tanks.

Not at all familiar	Slightly familiar	Somewhat familiar	Moderately familiar	Extremely familiar
1	2	3	4	5

Question 2:
Have you participated in this activity before? Circle:

YES / NO

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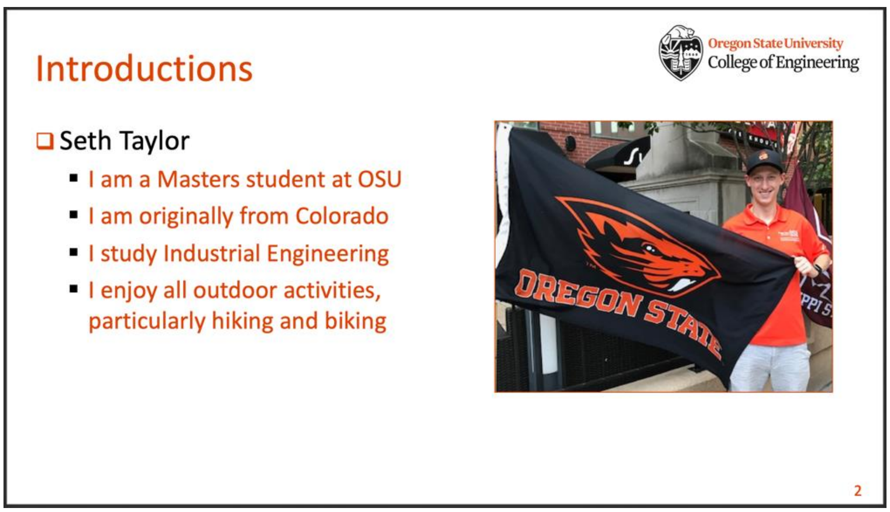
SMILE Middle and High School Challenge – April 26-27, 2019
Systems Thinking Activity

PART B

You recently purchased a fish tank. After two weeks, you notice the water is turning green in color.
Consider this problem as you complete the activity.

10.6 Research Study Presentation Slides



Oregon State University College of Engineering

What is Systems Thinking?

- A particular way of seeing the world.
- A particular way of thinking about the world.
- A tool for solving problems.

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Oregon State University College of Engineering

Systems Thinking Workshop Agenda

- Research Study Overview
  - Assent forms
- Warm-Up Activity
  - Fish tank system activity
- Systems Thinking Concepts Lesson
  - Fish tank system activity
- Conclusion

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Oregon State University College of Engineering

Research Study Overview

SMILE Middle and High School Challenge
April 26th – 27th, 2019
Oregon State University
Corvallis, Oregon

CaRSEM
Change and Reliable Systems Engineering and Management

Envision Believe Succeed
SMILE
SCIENCE & MATH INVESTIGATIVE LEARNING EXPERIENCES

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Research Study Overview

Oregon State University College of Engineering

- **Title:**
  - Measuring How Middle and High School Students Learn Systems Thinking
- **Study Team:**
  - Javier Calvo-Amodio (principal investigator)
  - Jay Well, Seth Taylor, & Malaia Jacobsen
- **Purpose:**
  - To understand how you, as a middle or high school student, learn systems thinking in order to improve systems thinking education and create better systems thinking lessons.

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Research Study Assent

Oregon State University College of Engineering

- We are inviting you to take part in a research study.
  - You do not have to be in the study if you do not want to.
- We are asking for your permission to use the fish tank system drawing that you create during this workshop in the research study and in future studies.
  - Your name will be removed from your drawing after we collect it.
  - You can still participate in the systems thinking workshop today even if you decide not to take part in the research study.

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Research Study Assent (cont.)

Oregon State University College of Engineering

- Please review pages 1-2 in your packet.
  - Research Study Assent Form
- All Students:
  - Write your name on page 2 where shown.
- Students who **do not** want to take part in the study:
  - Sign your name and write the date on page 2 where shown.

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Oregon State University
College of Engineering

Warm-Up Activity

SMILE Middle and High School Challenge
April 26th – 27th, 2019
Oregon State University
Corvallis, Oregon

CaRSEM
Change and Reliable Systems Engineering and Management

Envision Believe Succeed
SMILE
SCIENCE & MATH INVESTIGATIVE LEARNING EXPERIENCES

10

Warm-Up Activity

Oregon State University
College of Engineering

- On page 3 of your packet:
  - Problem Statement:
    - You recently purchased a fish tank. After two weeks, you notice the water is turning green in color. Consider this problem as you complete the activity.
  - Use the space provided to draw a fish tank system.
  - Think about elements, interactions, and the role/purpose of elements.

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Oregon State University
College of Engineering

Systems Thinking Concepts Lesson

SMILE Middle and High School Challenge
April 26th – 27th, 2019
Oregon State University
Corvallis, Oregon

CaRSEM
Change and Reliable Systems Engineering and Management

Envision Believe Succeed
SMILE
SCIENCE & MATH INVESTIGATIVE LEARNING EXPERIENCES

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Fish Tank System: Background

- Locate **PART A** on page 5 of your packet.
  - Answer Question 1:
    - Circle the **number** that best represents your familiarity with fish tanks.
  - Answer Question 2:
    - Circle **YES** or **NO** to indicate whether you have participated in this activity before.

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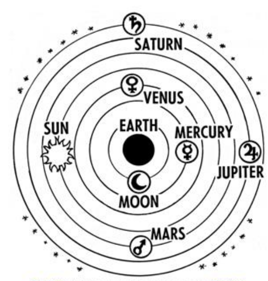
Systems Thinking Concepts

- #1: Distinctions
- #2: Relationships
- #3: Perspectives



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Systems Thinking Concept #1: **Distinctions**

- Distinctions are how we **draw or define the boundaries** of an element or a system of elements. This boundary defines **what is** and **what is not** that element or system.
- Shapes Example:

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Systems Thinking Concept #1: **Distinctions**

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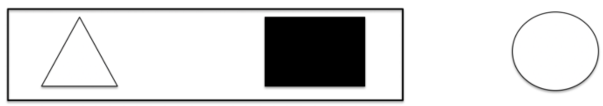
- Distinctions are how we **draw or define the boundaries** of an element or a system of elements. This boundary defines **what is** and **what is not** that element or system.
- Shapes Example:



System: Shapes with only straight edges

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Systems Thinking Concept #1: **Distinctions**

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- Distinctions are how we **draw or define the boundaries** of an element or a system of elements. This boundary defines **what is** and **what is not** that element or system.
- Shapes Example:

System: White shapes

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Fish Tank System: **Distinctions**

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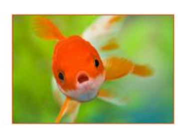
- Locate PART B on page 6 of your activity packet.



- Problem Statement:
  - You recently purchased a fish tank. After two weeks, you notice the water in the fish tank is turning green in color.
- Step 1 – **Elements**:
  - What ***elements*** are present in your fish tank system?
  - Draw and label each element in your drawing.

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Systems Thinking Concept #2: **Relationships**

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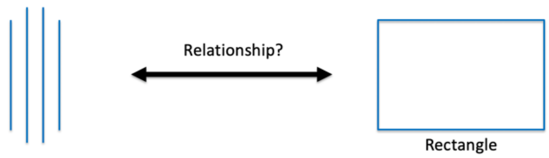
- ❑ Relationships help us understand how the **elements** within a system **interact** with each other.
- ❑ Shapes Example:



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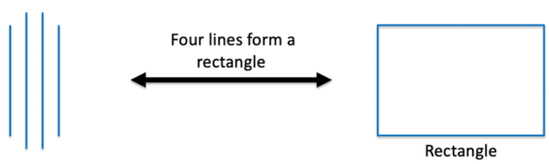
Systems Thinking Concept #2: **Relationships**

Oregon State University College of Engineering

- ❑ Relationships help us understand how the **elements** within a system **interact** with each other.
- ❑ Shapes Example:



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Fish Tank System: **Relationships**

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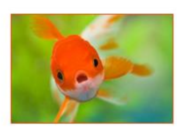
- ❑ Locate PART B on page 6 of your activity packet.



- ❑ Problem Statement:
  - You recently purchased a fish tank. After two weeks, you notice the water in the fish tank is turning green in color.
- ❑ Step 2 – **Interactions**:
  - What ***interactions*** are present in your fish tank system?
  - Draw and label each interaction in your drawing.

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Systems Thinking Concept #3: **Perspectives**

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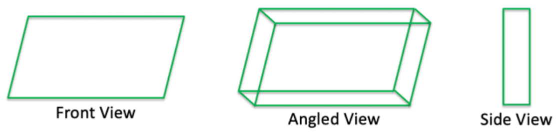
- A perspective is a particular **point of view** that we use to **understand** a system and elements in that system.
- Shapes Example:



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Fish Tank System: **Perspectives**

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- Locate PART B on page 6 of your activity packet.
- Problem Statement:
  - You recently purchased a fish tank. After two weeks, you notice the water in the fish tank is turning green in color.
- Step 3 – **Roles / Purposes**:
  - What is the ***role*** or ***purpose*** of each element in your fish tank system?
  - Label each element's role or purpose in your drawing.

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Conclusion

SMILE Middle and High School Challenge
April 26th – 27th, 2019
Oregon State University
Corvallis, Oregon

CaRSEM
Change and Reliable Systems Engineering and Management

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Systems Thinking Concepts

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- Distinctions
  - The ***elements*** of a system.
- Relationships
  - The ***interactions*** between elements in a system.
- Perspectives
  - The ***role*** or ***purpose*** of elements in a system.

Why Use Systems Thinking?

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- Helps us to define a problem.
- Allows us to view and think about a problem from multiple perspectives.
- Helps us to determine potential solutions to a problem.

Discussion Questions

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- Why is the problem statement important for effectively using systems thinking?
- How did you determine what elements were included in your fish tank system?
- Why is it important to consider the interactions between elements in your fish tank system?
  - Hint: Think about the problem statement...
- Do you think that your previous experience with fish tanks affected your perspective of your drawing?

[Additional] Discussion Questions

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- Problem Statement:
  - You recently purchased a fish tank. After two weeks, you notice the water is turning green in color.
  - Why is the problem statement important for effectively using systems thinking?

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[Additional] Discussion Questions

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- For systems thinking concept #1 – **distinctions**:
  - What were some common **elements** in your systems?
  - How did you determine what **elements** were included in your fish tank system?
  - How did you determine what **elements** were outside your fish tank system?

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[Additional] Discussion Questions

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- For systems thinking concept #2 – **relationships**:
  - How do the different elements in your fish tank system **interact** with each other?
  - Why is it important to consider the **interactions** between elements in your fish tank system?
    - Hint: Think about the problem statement...

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[Additional] Discussion Questions

- For systems thinking concept #3 – **perspectives**:
  - What kind of fish tank did you picture from the provided problem statement in the warm-up activity?
  - Do you think that your previous experience with fish tanks affected your perspective of your drawing?
  - How did you assign roles or purposes to the elements in your fish tank system?

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SMILE Middle and High School Challenge

Systems Thinking Workshop

Thank you for taking part in the research study!

Please turn in your activity packet before you leave!

CaRSEM
Change and Reliable Systems Engineering and Management

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Appendix E

11 Appendix E: Normal Probability Plots

The plot for the number of elements in Drawing A is presented in Figure 11-1.

The plot for the number of interactions in Drawing A is presented in Figure 11-2.

The plot for the number of roles/purposes in Drawing A is presented in Figure 11-3.

The plot for the total numbers in Drawing A is presented in Figure 11-4.

The plot for the number of elements in Drawing B is presented in Figure 11-5.

The plot for the number of interactions in Drawing B is presented in Figure 11-6.

The plot for the number of roles/purposes in Drawing B is presented in Figure 11-7.

The plot for the total numbers in Drawing B is presented in Figure 11-8.

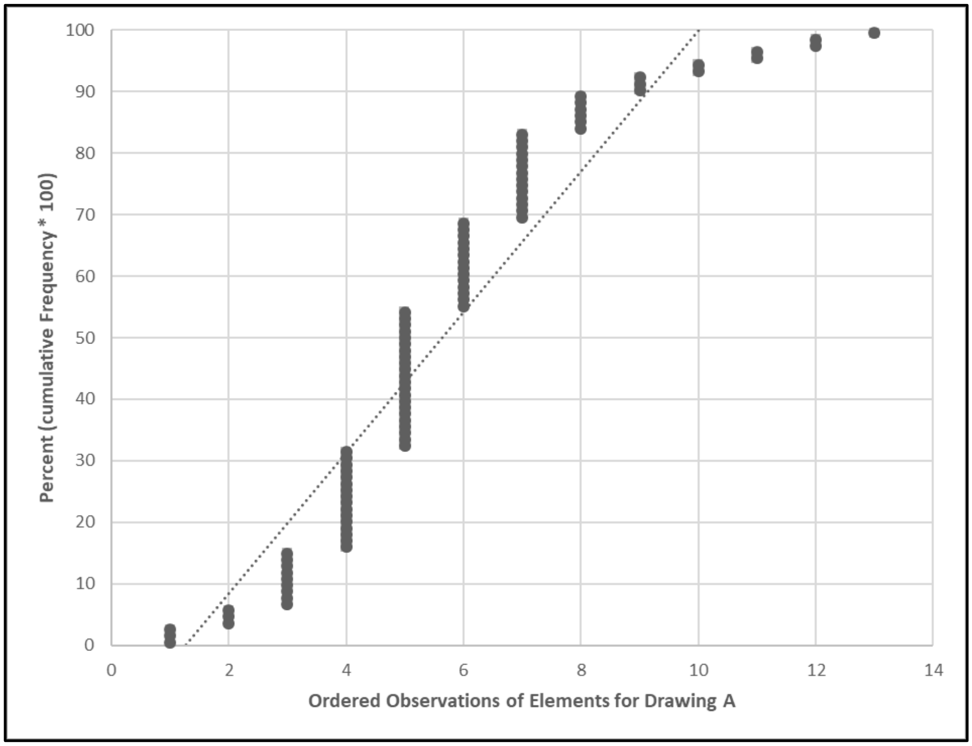

Figure 11-1: Normal Probability Plot for Drawing A – Elements

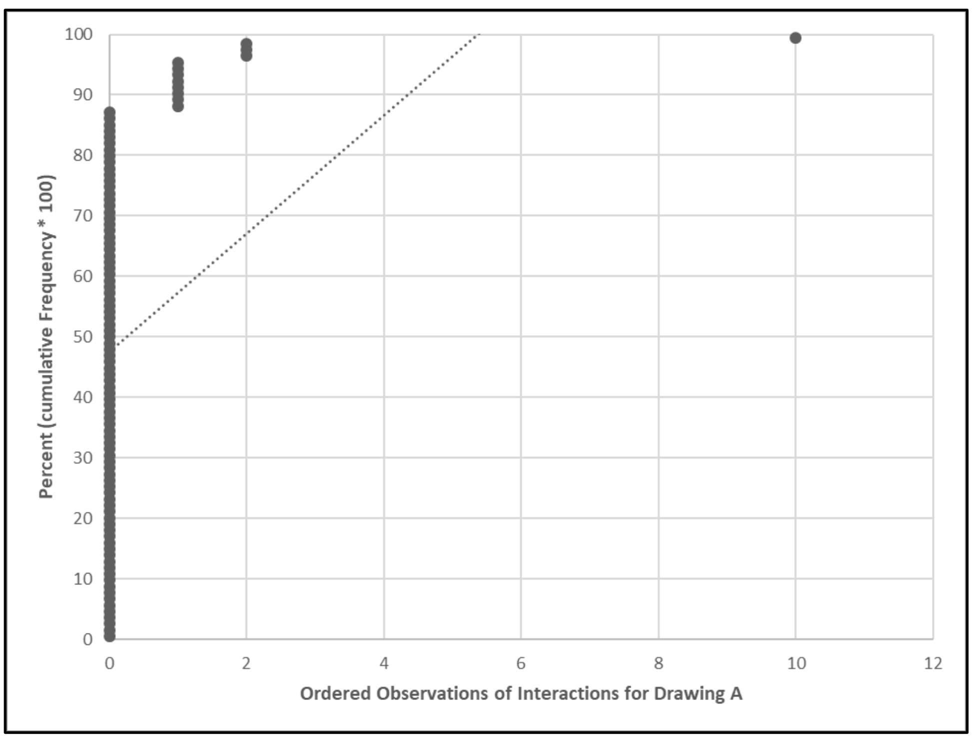

Figure 11-2: Normal Probability Plot for Drawing A – Interactions

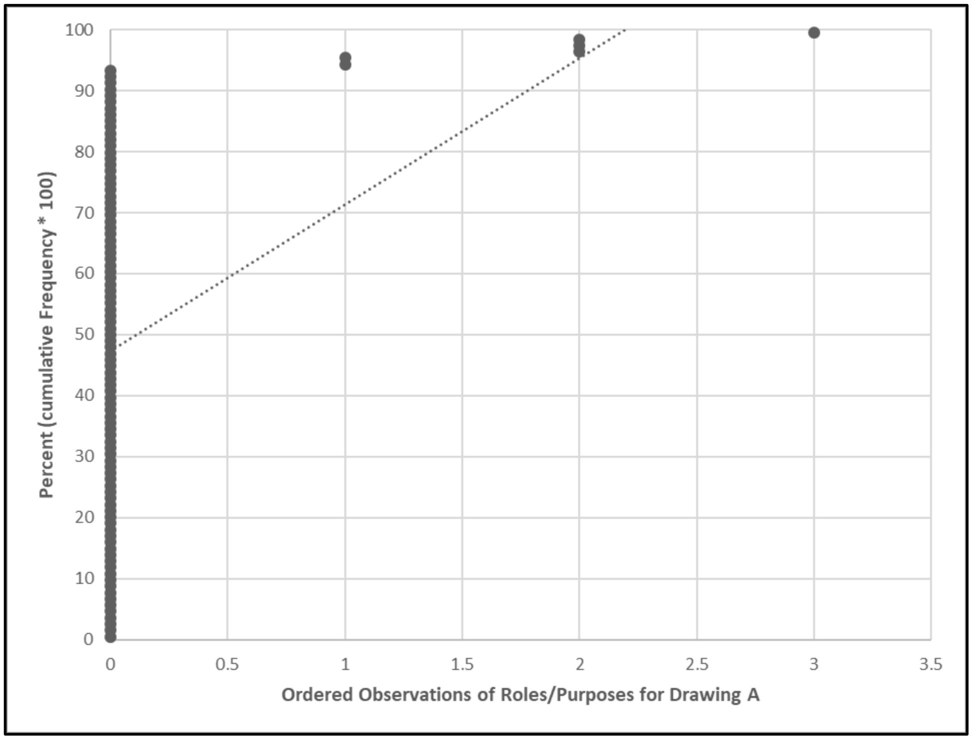

Figure 11-3: Normal Probability Plot for Drawing A – Roles/Purposes

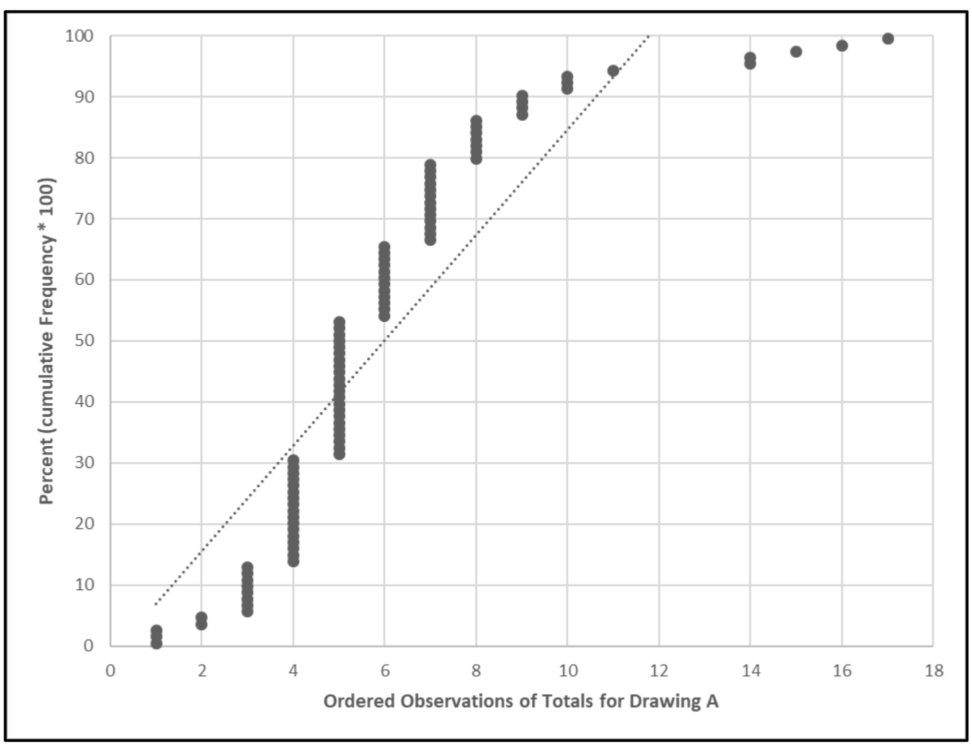

Figure 11-4: Normal Probability Plot for Drawing A – Totals

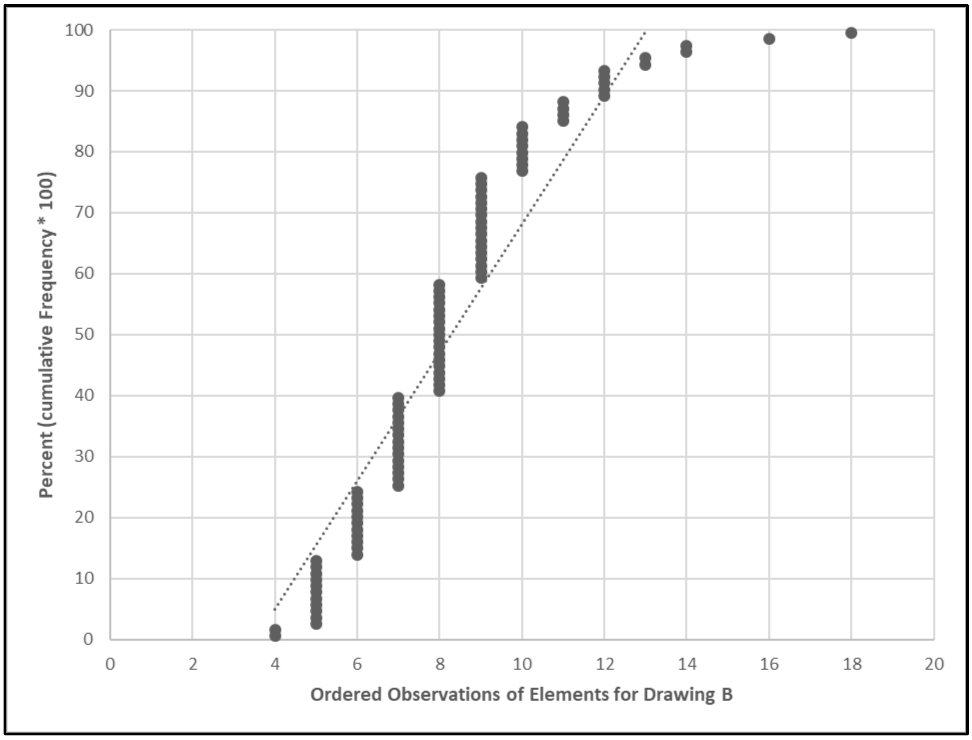

Figure 11-5: Normal Probability Plot for Drawing B – Elements

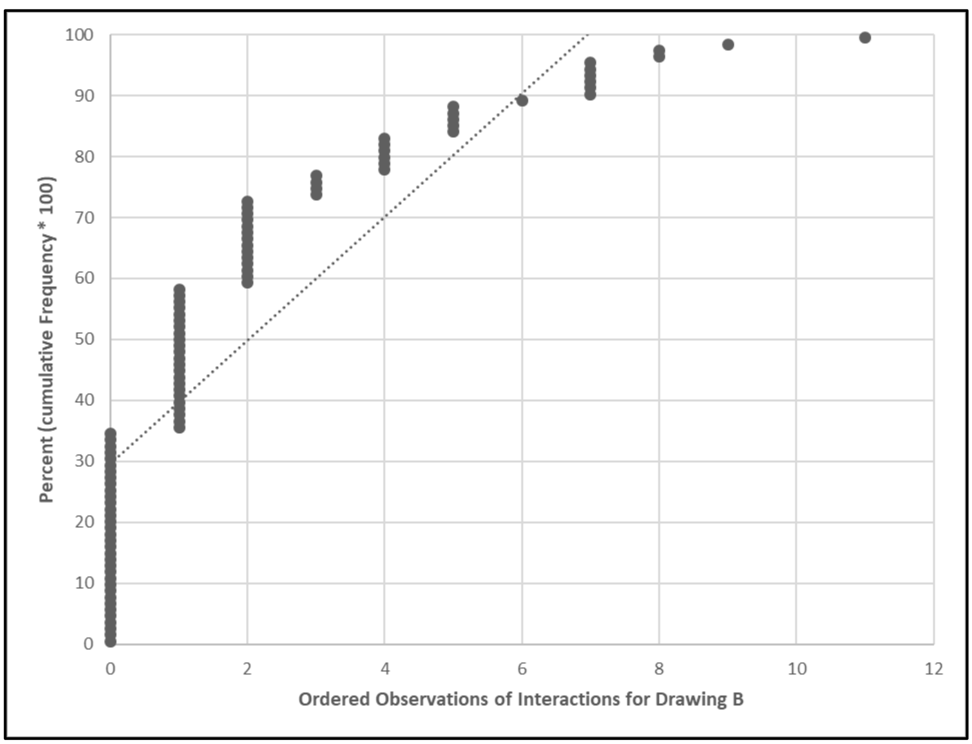

Figure 11-6: Normal Probability Plot for Drawing B – Interactions

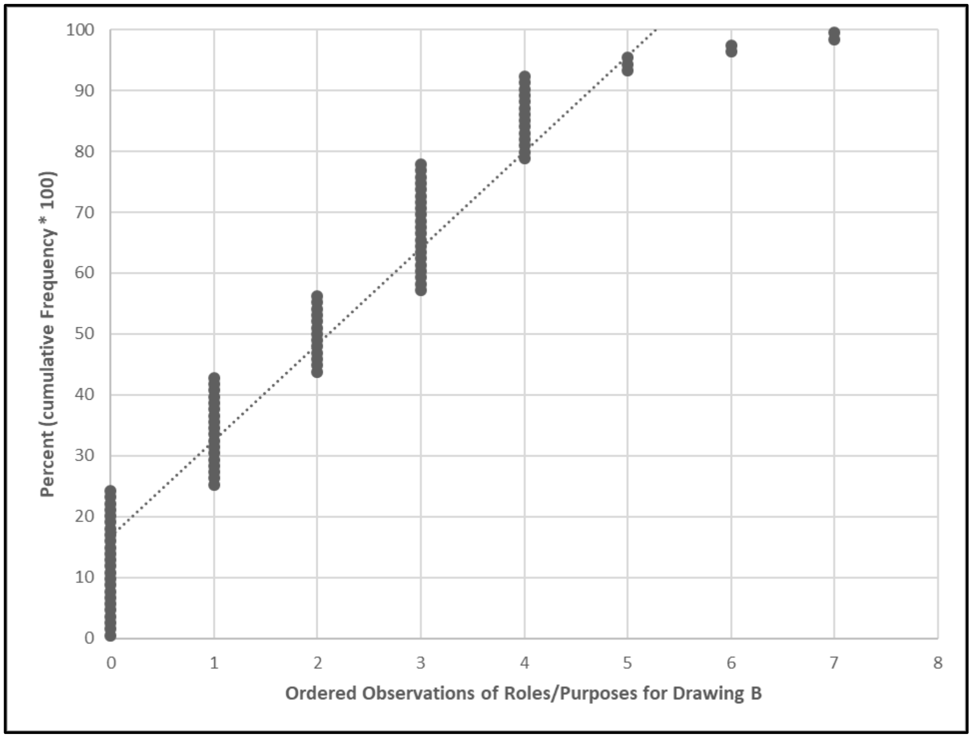

Figure 11-7: Normal Probability Plot for Drawing B – Roles/Purposes

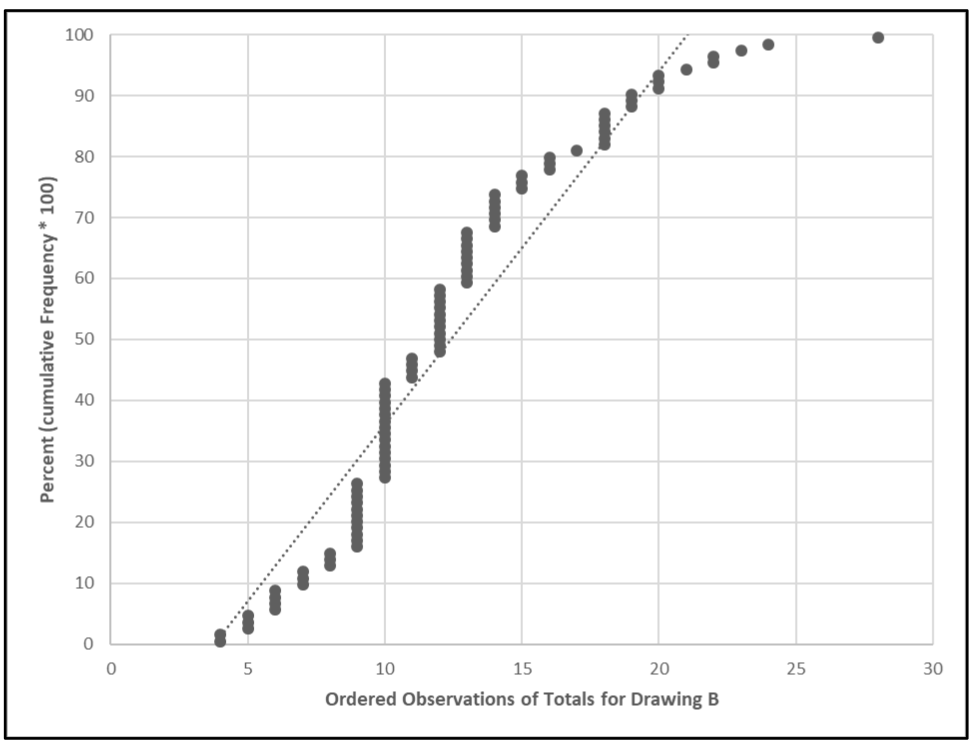

Figure 11-8: Normal Probability Plot for Drawing B – Totals

Appendix F

12 Appendix F: Tabulated Results

Note: For a glossary of variables, readers should refer to Table 9-1 in Appendix C: Glossary of Variables.

The tabulated results for elements are presented in Table 12-1.

The tabulated results for interactions are presented in Table 12-2.

The tabulated results for roles/purposes are presented in Table 12-3.

The tabulated results for totals are presented in Table 12-4.

The tabulated results for totals for middle school students are presented in Table 12-5.

The tabulated results for totals for high school students are presented in Table 12-6.

Table 12-1: Tabulated Results for Elements (E)

		x_{ijkl}						x_{ijkT}		z_{ijkT}	
j	F	x_{AjES}	x_{BjES}	x_{AjEL}	x_{BjEL}	x_{AjEC}	x_{BjEC}	x_{AjET}	x_{BjET}	z_{AjET}	z_{BjET}
1	4	3	3	2	3	0	0	5	6	7	9
2	1	3	3	0	2	0	0	3	5	3	7
3	2	3	3	3	3	0	1	6	7	9	12
4	3	2	2	2	3	0	0	4	5	6	8
5	1	3	3	0	2	0	0	3	5	3	7
6	4	3	3	0	1	0	0	3	4	3	5
7	2.5	1	3	1	6	0	0	2	9	3	15
8	4	3	3	5	5	0	0	8	8	13	13
9	5	3	3	4	4	0	0	7	7	11	11
10	1	3	3	2	6	0	1	5	10	7	18
11	3	3	3	2	7	1	0	6	10	10	17
12	4	3	3	4	3	0	1	7	7	11	12
13	3	2	2	2	4	0	1	4	7	6	13
14	2	2	3	2	7	0	2	4	12	6	23
15	3	3	3	6	8	0	1	9	12	15	22
16	2	3	3	3	4	1	1	7	8	12	14
17	2	3	3	3	2	0	0	6	5	9	7
18	2	3	3	2	5	0	0	5	8	7	13
19	2	2	3	2	4	0	1	4	8	6	14
20	5	2	3	3	6	0	0	5	9	8	15
21	5	2	3	3	6	0	1	5	10	8	18
22	3	3	3	6	6	0	0	9	9	15	15
23	2	2	3	4	6	0	0	6	9	10	15
24	2	3	3	4	4	1	1	8	8	14	14
25	4	1	3	3	5	0	2	4	10	7	19
26	3	3	3	4	8	0	0	7	11	11	19
27	4	3	3	1	4	0	0	4	7	5	11
28	2	3	3	2	5	0	0	5	8	7	13
29	5	1	2	0	2	0	1	1	5	1	9
30	2	3	3	2	5	0	0	5	8	7	13
31	2	2	3	3	4	0	0	5	7	8	11
32	1	2	2	3	3	0	1	5	6	8	11
33	3	3	3	4	2	1	1	8	6	14	10
34	2	3	3	6	5	2	0	11	8	21	13
35	3	2	3	2	2	0	0	4	5	6	7
36	4	3	3	4	4	0	0	7	7	11	11
37	3	3	3	0	2	0	0	3	5	3	7

		x_{ijkl}						x_{ijkT}		z_{ijkT}	
j	F	x_{AjES}	x_{BjES}	x_{AjEL}	x_{BjEL}	x_{AjEC}	x_{BjEC}	x_{AjET}	x_{BjET}	z_{AjET}	z_{BjET}
38	2	3	3	3	4	1	2	7	9	12	17
39	2	2	3	3	5	0	0	5	8	8	13
40	4	3	3	5	8	0	2	8	13	13	25
41	5	2	3	7	8	4	5	13	16	28	34
42	2	2	2	3	3	0	0	5	5	8	8
43	1	2	3	2	6	0	1	4	10	6	18
44	4	3	2	8	6	1	1	12	9	22	17
45	3	3	2	1	2	0	0	4	4	5	6
46	4	3	3	4	4	0	0	7	7	11	11
47	3	3	3	2	6	0	0	5	9	7	15
48	3	2	3	3	6	0	0	5	9	8	15
49	1	2	3	3	4	0	1	5	8	8	14
50	3	3	3	4	10	0	0	7	13	11	23
51	4	3	3	2	5	0	1	5	9	7	16
52	3	3	3	8	9	1	0	12	12	22	21
53	3	3	3	4	4	0	3	7	10	11	20
54	2	2	3	4	4	0	1	6	8	10	14
55	3	3	3	3	6	0	0	6	9	9	15
56	3	3	3	1	3	0	2	4	8	5	15
57	1	3	3	4	5	0	0	7	8	11	13
58	2	2	3	3	3	0	1	5	7	8	12
59	1	2	3	1	3	0	0	3	6	4	9
60	3	3	3	1	5	0	0	4	8	5	13
61	4	3	2	2	5	0	0	5	7	7	12
62	1	2	3	3	6	0	0	5	9	8	15
63	3	3	3	7	5	0	1	10	9	17	16
64	3	2	3	3	3	0	1	5	7	8	12
65	3	3	3	3	3	0	0	6	6	9	9
66	2	1	3	2	3	0	0	3	6	5	9
67	3	3	3	0	2	0	0	3	5	3	7
68	3	1	3	1	1	0	2	2	6	3	11
69	3	2	3	4	9	0	0	6	12	10	21
70	2	3	3	3	5	0	1	6	9	9	16
71	4	3	3	4	8	0	0	7	11	11	19
72	2	3	3	2	2	0	0	5	5	7	7
73	4	1	3	3	4	0	2	4	9	7	17
74	2	3	3	4	6	0	0	7	9	11	15
75	5	1	3	0	5	0	2	1	10	1	19

		x_{ijkl}						x_{ijkT}		z_{ijkT}	
j	F	x_{AjES}	x_{BjES}	x_{AjEL}	x_{BjEL}	x_{AjEC}	x_{BjEC}	x_{AjET}	x_{BjET}	z_{AjET}	z_{BjET}
76	3	3	3	6	5	0	1	9	9	15	16
77	3	2	3	5	5	0	0	7	8	12	13
78	3	3	3	3	6	0	0	6	9	9	15
79	4	3	3	5	4	0	1	8	8	13	14
80	3	3	3	2	4	0	1	5	8	7	14
81	3	3	3	6	14	1	1	10	18	18	34
82	3	1	3	0	2	0	0	1	5	1	7
83	1	1	3	1	9	1	2	3	14	6	27
84	4	1	3	1	3	0	0	2	6	3	9
85	3	2	3	2	4	0	0	4	7	6	11
86	2	3	3	3	3	0	1	6	7	9	12
87	5	2	3	6	9	0	2	8	14	14	27
88	3	1	3	2	3	0	0	3	6	5	9
89	4	2	3	2	2	0	1	4	6	6	10
90	2	2	3	2	5	0	0	4	8	6	13
91	4	3	3	2	7	1	1	6	11	10	20
92	2	3	3	1	4	0	0	4	7	5	11
93	3	3	3	6	6	2	2	11	11	21	21
94	2.5	2	3	4	6	0	1	6	10	10	18
95	2	3	3	2	4	0	0	5	7	7	11
96	2	3	3	3	3	0	0	6	6	9	9
97	3	2	3	5	7	0	2	7	12	12	23

Table 12-2: Tabulated Results for Interactions (I)

		x_{ijkl}						x_{ijkT}		z_{ijkT}	
j	F	x_{AjIS}	x_{BjIS}	x_{AjIL}	x_{BjIL}	x_{AjIC}	x_{BjIC}	x_{AjIT}	x_{BjIT}	z_{AjIT}	z_{BjIT}
1	4	0	5	0	0	0	0	0	5	0	5
2	1	0	0	0	1	0	0	0	1	0	2
3	2	0	0	0	0	0	0	0	0	0	0
4	3	0	1	0	0	0	0	0	1	0	1
5	1	0	0	0	0	0	0	0	0	0	0
6	4	0	0	0	0	0	0	0	0	0	0
7	2.5	0	0	0	0	0	0	0	0	0	0
8	4	0	1	0	1	0	0	0	2	0	3
9	5	0	0	0	0	0	0	0	0	0	0
10	1	0	0	0	0	0	0	0	0	0	0
11	3	10	7	0	4	0	0	10	11	10	15
12	4	0	0	0	2	0	0	0	2	0	4
13	3	0	0	0	1	0	0	0	1	0	2
14	2	0	0	0	1	0	0	0	1	0	2
15	3	0	1	0	8	0	0	0	9	0	17
16	2	0	0	1	1	0	0	1	1	2	2
17	2	0	0	0	1	0	0	0	1	0	2
18	2	0	0	0	0	0	0	0	0	0	0
19	2	0	0	0	1	0	0	0	1	0	2
20	5	0	0	0	1	0	0	0	1	0	2
21	5	0	0	0	0	0	0	0	0	0	0
22	3	0	0	0	2	0	0	0	2	0	4
23	2	0	0	0	0	0	0	0	0	0	0
24	2	0	0	0	2	0	0	0	2	0	4
25	4	0	0	0	0	0	1	0	1	0	3
26	3	0	2	0	5	0	0	0	7	0	12
27	4	0	0	0	0	0	0	0	0	0	0
28	2	0	3	0	0	0	0	0	3	0	3
29	5	0	0	0	0	0	0	0	0	0	0
30	2	0	0	0	1	0	0	0	1	0	2
31	2	0	0	0	2	0	0	0	2	0	4
32	1	0	0	0	0	0	0	0	0	0	0
33	3	0	0	0	2	0	0	0	2	0	4
34	2	0	0	0	7	2	0	2	7	6	14
35	3	0	4	0	0	0	0	0	4	0	4
36	4	0	0	0	5	0	0	0	5	0	10
37	3	0	0	0	0	0	0	0	0	0	0

		x_{ijkl}						x_{ijkT}		z_{ijkT}	
j	F	x_{AjIS}	x_{BjIS}	x_{AjIL}	x_{BjIL}	x_{AjIC}	x_{BjIC}	x_{AjIT}	x_{BjIT}	z_{AjIT}	z_{BjIT}
38	2	0	2	0	5	0	0	0	7	0	12
39	2	0	4	0	0	0	0	0	4	0	4
40	4	1	7	0	0	0	0	1	7	1	7
41	5	0	0	2	6	0	0	2	6	4	12
42	2	0	0	1	1	0	0	1	1	2	2
43	1	0	0	0	1	0	0	0	1	0	2
44	4	0	0	0	1	0	0	0	1	0	2
45	3	0	0	0	0	0	0	0	0	0	0
46	4	0	0	0	0	0	0	0	0	0	0
47	3	0	0	0	7	0	0	0	7	0	14
48	3	0	0	0	0	0	0	0	0	0	0
49	1	0	0	0	0	0	0	0	0	0	0
50	3	0	0	0	3	0	0	0	3	0	6
51	4	0	0	0	1	0	0	0	1	0	2
52	3	0	0	0	0	0	0	0	0	0	0
53	3	0	0	0	4	0	0	0	4	0	8
54	2	0	1	0	0	0	0	0	1	0	1
55	3	0	0	0	3	0	1	0	4	0	9
56	3	0	0	0	2	0	0	0	2	0	4
57	1	0	0	0	0	0	0	0	0	0	0
58	2	0	1	0	1	0	0	0	2	0	3
59	1	0	0	1	0	0	1	1	1	2	3
60	3	0	0	0	0	0	0	0	0	0	0
61	4	0	0	0	1	0	0	0	1	0	2
62	1	0	0	0	2	0	0	0	2	0	4
63	3	0	6	0	1	0	0	0	7	0	8
64	3	0	2	0	0	0	0	0	2	0	2
65	3	0	1	0	0	0	0	0	1	0	1
66	2	0	0	0	2	0	0	0	2	0	4
67	3	0	0	0	0	0	0	0	0	0	0
68	3	0	0	0	3	0	0	0	3	0	6
69	3	0	0	0	8	0	0	0	8	0	16
70	2	0	0	0	0	0	0	0	0	0	0
71	4	0	0	0	1	0	1	0	2	0	5
72	2	0	0	0	0	0	0	0	0	0	0
73	4	0	0	0	0	0	0	0	0	0	0
74	2	2	5	0	0	0	0	2	5	2	5
75	5	0	0	0	0	0	0	0	0	0	0

		x_{ijkl}						x_{ijkT}		z_{ijkT}	
j	F	x_{AjIS}	x_{BjIS}	x_{AjIL}	x_{BjIL}	x_{AjIC}	x_{BjIC}	x_{AjIT}	x_{BjIT}	z_{AjIT}	z_{BjIT}
76	3	1	0	0	1	0	0	1	1	1	2
77	3	0	0	0	0	0	0	0	0	0	0
78	3	0	0	0	3	0	0	0	3	0	6
79	4	0	0	0	0	0	0	0	0	0	0
80	3	0	0	0	5	0	0	0	5	0	10
81	3	0	0	0	0	0	0	0	0	0	0
82	3	0	1	0	0	0	0	0	1	0	1
83	1	0	0	0	2	0	0	0	2	0	4
84	4	0	0	1	2	0	0	1	2	2	4
85	3	0	0	0	0	0	0	0	0	0	0
86	2	0	0	0	3	0	1	0	4	0	9
87	5	0	0	0	0	0	0	0	0	0	0
88	3	0	0	0	0	0	0	0	0	0	0
89	4	0	0	1	1	0	0	1	1	2	2
90	2	0	0	0	0	0	0	0	0	0	0
91	4	0	0	0	4	0	0	0	4	0	8
92	2	0	0	0	0	0	0	0	0	0	0
93	3	0	0	0	0	0	0	0	0	0	0
94	2.5	0	0	0	1	1	0	1	1	3	2
95	2	0	0	0	0	0	1	0	1	0	3
96	2	0	2	0	3	0	0	0	5	0	8
97	3	0	8	0	0	0	0	0	8	0	8

Table 12-3: Tabulated Results for Roles/Purposes (R)

		x_{ijkl}						x_{ijkT}		z_{ijkT}	
j	F	x_{AjRS}	x_{BjRS}	x_{AjRL}	x_{BjRL}	x_{AjRC}	x_{BjRC}	x_{AjRT}	x_{BjRT}	z_{AjRT}	z_{BjRT}
1	4	0	0	0	1	0	0	0	1	0	2
2	1	0	0	0	1	0	0	0	1	0	2
3	2	0	1	0	2	0	0	0	3	0	5
4	3	0	0	0	0	0	0	0	0	0	0
5	1	0	0	0	0	0	0	0	0	0	0
6	4	0	0	0	0	0	0	0	0	0	0
7	2.5	0	1	0	0	0	0	0	1	0	1
8	4	0	0	0	3	0	0	0	3	0	6
9	5	0	2	0	1	0	0	0	3	0	4
10	1	0	0	0	0	0	0	0	0	0	0
11	3	0	0	0	2	0	0	0	2	0	4
12	4	0	0	0	4	0	0	0	4	0	8
13	3	0	0	0	0	0	0	0	0	0	0
14	2	0	0	0	3	0	0	0	3	0	6
15	3	0	1	0	6	0	0	0	7	0	13
16	2	0	0	0	0	0	0	0	0	0	0
17	2	0	0	0	0	0	0	0	0	0	0
18	2	0	3	0	2	0	0	0	5	0	7
19	2	0	0	0	0	0	0	0	0	0	0
20	5	0	2	0	0	0	0	0	2	0	2
21	5	0	0	0	0	0	0	0	0	0	0
22	3	0	0	0	1	0	0	0	1	0	2
23	2	0	0	0	2	0	0	0	2	0	4
24	2	0	0	0	2	0	0	0	2	0	4
25	4	0	1	0	1	0	0	0	2	0	3
26	3	0	2	0	2	0	0	0	4	0	6
27	4	0	1	0	2	0	0	0	3	0	5
28	2	0	2	0	1	0	0	0	3	0	4
29	5	0	0	0	0	0	0	0	0	0	0
30	2	0	0	0	1	0	0	0	1	0	2
31	2	0	2	0	1	0	0	0	3	0	4
32	1	0	0	0	1	0	0	0	1	0	2
33	3	0	0	0	1	0	0	0	1	0	2
34	2	0	2	1	3	0	0	1	5	2	8
35	3	0	3	0	1	0	0	0	4	0	5
36	4	0	0	0	0	0	0	0	0	0	0
37	3	0	0	0	4	0	0	0	4	0	8

		x_{ijkl}						x_{ijkT}		z_{ijkT}	
j	F	x_{AjRS}	x_{BjRS}	x_{AjRL}	x_{BjRL}	x_{AjRC}	x_{BjRC}	x_{AjRT}	x_{BjRT}	z_{AjRT}	z_{BjRT}
38	2	0	0	0	2	0	0	0	2	0	4
39	2	0	1	0	2	0	0	0	3	0	5
40	4	0	0	0	1	0	0	0	1	0	2
41	5	0	0	2	0	0	0	2	0	4	0
42	2	0	0	0	1	0	0	0	1	0	2
43	1	0	0	0	2	0	0	0	2	0	4
44	4	0	0	2	3	0	0	2	3	4	6
45	3	0	0	0	0	0	0	0	0	0	0
46	4	0	0	0	3	0	0	0	3	0	6
47	3	0	2	0	2	0	0	0	4	0	6
48	3	0	1	0	0	0	0	0	1	0	1
49	1	0	0	0	1	0	0	0	1	0	2
50	3	0	1	0	2	0	0	0	3	0	5
51	4	0	0	0	0	0	0	0	0	0	0
52	3	0	0	3	4	0	0	3	4	6	8
53	3	0	2	0	2	0	0	0	4	0	6
54	2	0	0	0	3	0	0	0	3	0	6
55	3	0	0	0	1	0	0	0	1	0	2
56	3	0	0	0	2	0	0	0	2	0	4
57	1	0	1	0	2	0	0	0	3	0	5
58	2	0	3	0	0	0	0	0	3	0	3
59	1	0	0	0	3	0	0	0	3	0	6
60	3	0	0	0	0	0	0	0	0	0	0
61	4	0	0	0	1	0	0	0	1	0	2
62	1	0	3	0	1	0	0	0	4	0	5
63	3	0	0	0	2	0	0	0	2	0	4
64	3	0	0	0	1	0	0	0	1	0	2
65	3	0	0	0	3	0	0	0	3	0	6
66	2	0	1	0	4	0	0	0	5	0	9
67	3	0	0	0	1	0	0	0	1	0	2
68	3	0	0	0	0	0	0	0	0	0	0
69	3	0	1	0	3	0	0	0	4	0	7
70	2	0	0	0	0	0	0	0	0	0	0
71	4	0	0	0	3	0	0	0	3	0	6
72	2	0	0	0	0	0	0	0	0	0	0
73	4	0	0	0	0	0	0	0	0	0	0
74	2	0	0	0	4	0	0	0	4	0	8
75	5	0	0	0	0	0	0	0	0	0	0

		x_{ijkl}						x_{ijkT}		z_{ijkT}	
j	F	x_{AjRS}	x_{BjRS}	x_{AjRL}	x_{BjRL}	x_{AjRC}	x_{BjRC}	x_{AjRT}	x_{BjRT}	z_{AjRT}	z_{BjRT}
76	3	0	1	0	1	0	0	0	2	0	3
77	3	0	1	0	5	0	0	0	6	0	11
78	3	0	2	0	1	0	0	0	3	0	4
79	4	0	0	0	4	0	0	0	4	0	8
80	3	0	0	0	1	0	0	0	1	0	2
81	3	0	0	0	0	0	0	0	0	0	0
82	3	0	0	0	0	0	0	0	0	0	0
83	1	0	2	0	1	0	0	0	3	0	4
84	4	0	0	1	2	0	0	1	2	2	4
85	3	0	1	0	3	0	0	0	4	0	7
86	2	0	1	0	1	0	0	0	2	0	3
87	5	0	0	0	0	0	0	0	0	0	0
88	3	0	0	0	3	0	0	0	3	0	6
89	4	0	0	0	1	0	0	0	1	0	2
90	2	0	0	0	2	0	0	0	2	0	4
91	4	0	0	0	4	0	0	0	4	0	8
92	2	0	1	0	3	0	0	0	4	0	7
93	3	0	2	0	5	0	0	0	7	0	12
94	2.5	0	1	0	5	0	0	0	6	0	11
95	2	0	0	0	1	0	0	0	1	0	2
96	2	0	0	2	3	0	0	2	3	4	6
97	3	0	0	0	0	0	0	0	0	0	0

Table 12-4: Tabulated Results for Totals (T)

		x_{ijlT}						x_{ijT}		z_{ijT}	
j	F	x_{AjST}	x_{BjST}	x_{AjLT}	x_{BjLT}	x_{AjCT}	x_{BjCT}	x_{AjT}	x_{BjT}	z_{AjT}	z_{BjT}
1	4	3	8	2	4	0	0	5	12	7	16
2	1	3	3	0	4	0	0	3	7	3	11
3	2	3	4	3	5	0	1	6	10	9	17
4	3	2	3	2	3	0	0	4	6	6	9
5	1	3	3	0	2	0	0	3	5	3	7
6	4	3	3	0	1	0	0	3	4	3	5
7	2.5	1	4	1	6	0	0	2	10	3	16
8	4	3	4	5	9	0	0	8	13	13	22
9	5	3	5	4	5	0	0	7	10	11	15
10	1	3	3	2	6	0	1	5	10	7	18
11	3	13	10	2	13	1	0	16	23	20	36
12	4	3	3	4	9	0	1	7	13	11	24
13	3	2	2	2	5	0	1	4	8	6	15
14	2	2	3	2	11	0	2	4	16	6	31
15	3	3	5	6	22	0	1	9	28	15	52
16	2	3	3	4	5	1	1	8	9	14	16
17	2	3	3	3	3	0	0	6	6	9	9
18	2	3	6	2	7	0	0	5	13	7	20
19	2	2	3	2	5	0	1	4	9	6	16
20	5	2	5	3	7	0	0	5	12	8	19
21	5	2	3	3	6	0	1	5	10	8	18
22	3	3	3	6	9	0	0	9	12	15	21
23	2	2	3	4	8	0	0	6	11	10	19
24	2	3	3	4	8	1	1	8	12	14	22
25	4	1	4	3	6	0	3	4	13	7	25
26	3	3	7	4	15	0	0	7	22	11	37
27	4	3	4	1	6	0	0	4	10	5	16
28	2	3	8	2	6	0	0	5	14	7	20
29	5	1	2	0	2	0	1	1	5	1	9
30	2	3	3	2	7	0	0	5	10	7	17
31	2	2	5	3	7	0	0	5	12	8	19
32	1	2	2	3	4	0	1	5	7	8	13
33	3	3	3	4	5	1	1	8	9	14	16
34	2	3	5	7	15	4	0	14	20	29	35
35	3	2	10	2	3	0	0	4	13	6	16
36	4	3	3	4	9	0	0	7	12	11	21
37	3	3	3	0	6	0	0	3	9	3	15

		x_{ijlT}						x_{ijT}		z_{ijT}	
j	F	x_{AjST}	x_{BjST}	x_{AjLT}	x_{BjLT}	x_{AjCT}	x_{BjCT}	x_{AjT}	x_{BjT}	z_{AjT}	z_{BjT}
38	2	3	5	3	11	1	2	7	18	12	33
39	2	2	8	3	7	0	0	5	15	8	22
40	4	4	10	5	9	0	2	9	21	14	34
41	5	2	3	11	14	4	5	17	22	36	46
42	2	2	2	4	5	0	0	6	7	10	12
43	1	2	3	2	9	0	1	4	13	6	24
44	4	3	2	10	10	1	1	14	13	26	25
45	3	3	2	1	2	0	0	4	4	5	6
46	4	3	3	4	7	0	0	7	10	11	17
47	3	3	5	2	15	0	0	5	20	7	35
48	3	2	4	3	6	0	0	5	10	8	16
49	1	2	3	3	5	0	1	5	9	8	16
50	3	3	4	4	15	0	0	7	19	11	34
51	4	3	3	2	6	0	1	5	10	7	18
52	3	3	3	11	13	1	0	15	16	28	29
53	3	3	5	4	10	0	3	7	18	11	34
54	2	2	4	4	7	0	1	6	12	10	21
55	3	3	3	3	10	0	1	6	14	9	26
56	3	3	3	1	7	0	2	4	12	5	23
57	1	3	4	4	7	0	0	7	11	11	18
58	2	2	7	3	4	0	1	5	12	8	18
59	1	2	3	2	6	0	1	4	10	6	18
60	3	3	3	1	5	0	0	4	8	5	13
61	4	3	2	2	7	0	0	5	9	7	16
62	1	2	6	3	9	0	0	5	15	8	24
63	3	3	9	7	8	0	1	10	18	17	28
64	3	2	5	3	4	0	1	5	10	8	16
65	3	3	4	3	6	0	0	6	10	9	16
66	2	1	4	2	9	0	0	3	13	5	22
67	3	3	3	0	3	0	0	3	6	3	9
68	3	1	3	1	4	0	2	2	9	3	17
69	3	2	4	4	20	0	0	6	24	10	44
70	2	3	3	3	5	0	1	6	9	9	16
71	4	3	3	4	12	0	1	7	16	11	30
72	2	3	3	2	2	0	0	5	5	7	7
73	4	1	3	3	4	0	2	4	9	7	17
74	2	5	8	4	10	0	0	9	18	13	28
75	5	1	3	0	5	0	2	1	10	1	19

		x_{ijlT}						x_{ijT}		z_{ijT}	
j	F	x_{AjST}	x_{BjST}	x_{AjLT}	x_{BjLT}	x_{AjCT}	x_{BjCT}	x_{AjT}	x_{BjT}	z_{AjT}	z_{BjT}
76	3	4	4	6	7	0	1	10	12	16	21
77	3	2	4	5	10	0	0	7	14	12	24
78	3	3	5	3	10	0	0	6	15	9	25
79	4	3	3	5	8	0	1	8	12	13	22
80	3	3	3	2	10	0	1	5	14	7	26
81	3	3	3	6	14	1	1	10	18	18	34
82	3	1	4	0	2	0	0	1	6	1	8
83	1	1	5	1	12	1	2	3	19	6	35
84	4	1	3	3	7	0	0	4	10	7	17
85	3	2	4	2	7	0	0	4	11	6	18
86	2	3	4	3	7	0	2	6	13	9	24
87	5	2	3	6	9	0	2	8	14	14	27
88	3	1	3	2	6	0	0	3	9	5	15
89	4	2	3	3	4	0	1	5	8	8	14
90	2	2	3	2	7	0	0	4	10	6	17
91	4	3	3	2	15	1	1	6	19	10	36
92	2	3	4	1	7	0	0	4	11	5	18
93	3	3	5	6	11	2	2	11	18	21	33
94	2.5	2	4	4	12	1	1	7	17	13	31
95	2	3	3	2	5	0	1	5	9	7	16
96	2	3	5	5	9	0	0	8	14	13	23
97	3	2	11	5	7	0	2	7	20	12	31

Table 12-5: Tabulated Results for Totals for Middle School (MS) Students

		x_{ijlT}			x_{ijT}		z_{ijT}	
j	F	x_{BjST}	x_{BjLT}	x_{BjCT}	x_{BjT}	x_{BAjT}	z_{BjT}	z_{BAjT}
1	4	8	4	0	12	7	16	9
2	1	3	4	0	7	4	11	8
4	3	3	3	0	6	2	9	3
5	1	3	2	0	5	2	7	4
7	2.5	4	6	0	10	8	16	13
8	4	4	9	0	13	5	22	9
10	1	3	6	1	10	5	18	11
12	4	3	9	1	13	6	24	13
15	3	5	22	1	28	19	52	37
20	5	5	7	0	12	7	19	11
21	5	3	6	1	10	5	18	10
23	2	3	8	0	11	5	19	9
24	2	3	8	1	12	4	22	8
28	2	8	6	0	14	9	20	13
29	5	2	2	1	5	4	9	8
30	2	3	7	0	10	5	17	10
32	1	2	4	1	7	2	13	5
37	3	3	6	0	9	6	15	12
39	2	8	7	0	15	10	22	14
45	3	2	2	0	4	0	6	1
46	4	3	7	0	10	3	17	6
48	3	4	6	0	10	5	16	8
52	3	3	13	0	16	1	29	1
53	3	5	10	3	18	11	34	23
55	3	3	10	1	14	8	26	17
56	3	3	7	2	12	8	23	18
57	1	4	7	0	11	4	18	7
59	1	3	6	1	10	6	18	12
60	3	3	5	0	8	4	13	8
62	1	6	9	0	15	10	24	16
64	3	5	4	1	10	5	16	8
65	3	4	6	0	10	4	16	7
68	3	3	4	2	9	7	17	14
70	2	3	5	1	9	3	16	7
71	4	3	12	1	16	9	30	19
73	4	3	4	2	9	5	17	10
75	5	3	5	2	10	9	19	18

		x_{ijlT}			x_{ijT}		z_{ijT}	
j	**F**	x_{BjST}	x_{BjLT}	x_{BjCT}	x_{BjT}	x_{BAjT}	z_{BjT}	z_{BAjT}
78	3	5	10	0	15	9	25	16
79	4	3	8	1	12	4	22	9
80	3	3	10	1	14	9	26	19
84	4	3	7	0	10	6	17	10
90	2	3	7	0	10	6	17	11

Table 12-6: Tabulated Results for Totals for High School (HS) Students

		x_{ijlT}			x_{ijT}		z_{ijT}	
j	F	x_{BjST}	x_{BjLT}	x_{BjCT}	x_{BjT}	x_{BAjT}	z_{BjT}	z_{BAjT}
3	2	4	5	1	10	4	17	8
6	4	3	1	0	4	1	5	2
9	5	5	5	0	10	3	15	4
11	3	10	13	0	23	7	36	16
13	3	2	5	1	8	4	15	9
14	2	3	11	2	16	12	31	25
16	2	3	5	1	9	1	16	2
17	2	3	3	0	6	0	9	0
18	2	6	7	0	13	8	20	13
19	2	3	5	1	9	5	16	10
22	3	3	9	0	12	3	21	6
25	4	4	6	3	13	9	25	18
26	3	7	15	0	22	15	37	26
27	4	4	6	0	10	6	16	11
31	2	5	7	0	12	7	19	11
33	3	3	5	1	9	1	16	2
34	2	5	15	0	20	6	35	6
35	3	10	3	0	13	9	16	10
36	4	3	9	0	12	5	21	10
38	2	5	11	2	18	11	33	21
40	4	10	9	2	21	12	34	20
41	5	3	14	5	22	5	46	10
42	2	2	5	0	7	1	12	2
43	1	3	9	1	13	9	24	18
44	4	2	10	1	13	-1	25	-1
47	3	5	15	0	20	15	35	28
49	1	3	5	1	9	4	16	8
50	3	4	15	0	19	12	34	23
51	4	3	6	1	10	5	18	11
54	2	4	7	1	12	6	21	11
58	2	7	4	1	12	7	18	10
61	4	2	7	0	9	4	16	9
63	3	9	8	1	18	8	28	11
66	2	4	9	0	13	10	22	17
67	3	3	3	0	6	3	9	6
69	3	4	20	0	24	18	44	34
72	2	3	2	0	5	0	7	0

		x_{ijlT}			x_{ijT}		z_{ijT}	
j	**F**	x_{BjST}	x_{BjLT}	x_{BjCT}	x_{BjT}	x_{BAjT}	z_{BjT}	z_{BAjT}
74	2	8	10	0	18	9	28	15
76	3	4	7	1	12	2	21	5
77	3	4	10	0	14	7	24	12
81	3	3	14	1	18	8	34	16
82	3	4	2	0	6	5	8	7
83	1	5	12	2	19	16	35	29
85	3	4	7	0	11	7	18	12
86	2	4	7	2	13	7	24	15
87	5	3	9	2	14	6	27	13
88	3	3	6	0	9	6	15	10
89	4	3	4	1	8	3	14	6
91	4	3	15	1	19	13	36	26
92	2	4	7	0	11	7	18	13
93	3	5	11	2	18	7	33	12
94	2.5	4	12	1	17	10	31	18
95	2	3	5	1	9	4	16	9
96	2	5	9	0	14	6	23	10
97	3	11	7	2	20	13	31	19

Appendix G

13 Appendix G: ANOVA Matrices

Note: For a glossary of variables, readers should refer to Table 9-1 in Appendix C: Glossary of Variables.

The matrix for group differences for elements is presented in Table 13-1.

The matrix for group differences for interactions is presented in Table 13-2.

The matrix for group differences for roles/purposes is presented in Table 13-3.

The matrix for group differences for totals is presented in Table 13-4.

The matrix for instructor differences for elements is presented in Table 13-5.

The matrix for instructor differences for interactions is presented in Table 13-6.

The matrix for instructor differences for roles/purposes is presented in Table 13-7.

The matrix for instructor differences for totals is presented in Table 13-8.

Table 13-1: Paired Difference in Total Element Scores by Group

Group (*w*)	**Student Number in Each Group (*v*)**													$d_{z_{w\cdot}}$	$\bar{d}_{z_{w\cdot}}$	n_w
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**			
(1) HS-1	6	6	0	8	6	4	4	4	21	3	4	6		72	6.00	12
(2) HS-2	0	8	8	12	9	11	0	1	6	5	8	0		68	5.67	12
(3) HS-3	3	2	-2	0	3	-8	1	0	5	-1	4	1	4	12	0.92	13
(4) HS-4	17	6	12	-4	12	12	-5	4	16	13	0			83	7.55	11
(5) HS-5	2	7	7	5	10	4	11							46	6.57	7
(6) MS-1	2	8	3	6	4	18	6							47	6.71	7
(7) MS-2	12	7	0	6	5	-1	2	8	0	6				45	4.50	10
(8) MS-3	2	11	7	10	7	9	10	5	8	7	10	7		93	7.75	12
(9) MS-4	4	4	0	1	5	6	4	1	0	7	8	1	7	48	3.69	13

Table 13-2: Paired Difference in Total Interaction Scores by Group

Group (*w*)	**Student Number in Each Group (*v*)**													$d_{z_{w\cdot}}$	$\bar{d}_{z_{w\cdot}}$	n_w
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**			
(1) HS-1	0	8	0	14	0	3	4	3	4	9	0	0		45	3.75	12
(2) HS-2	0	2	12	6	2	16	0	0	1	0	-1	8		46	3.83	12
(3) HS-3	0	0	2	4	4	8	4	10	12	8	0	1	0	53	4.08	13
(4) HS-4	2	0	3	4	6	2	2	1	0	0	0			20	1.82	11
(5) HS-5	0	5	2	2	8	3	8							28	4.00	7
(6) MS-1	5	0	0	9	2	0	2							18	2.57	7
(7) MS-2	0	17	4	3	4	0	0	0	1	6				35	3.50	10
(8) MS-3	1	0	2	0	0	8	4	1	6	0	0	0		22	1.83	12
(9) MS-4	2	0	3	4	0	2	0	0	0	4	5	0	10	30	2.31	13

Table 13-3: Paired Difference in Total Role/Purpose Scores by Group

Group (*w*)	**Student Number in Each Group (*v*)**													$d_{z_{w\cdot}}$	$\bar{d}_{z_{w\cdot}}$	n_w
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**			
(1) HS-1	5	-4	2	6	2	3	9	8	4	3	2	7		47	3.92	12
(2) HS-2	4	0	6	5	0	7	0	11	0	7	11	2		53	4.42	12
(3) HS-3	5	0	0	2	4	6	5	0	4	4	2	3	6	41	3.15	13
(4) HS-4	6	7	3	2	2	4	2	6	0	0	12			44	4.00	11
(5) HS-5	0	4	0	2	8	2	0							16	2.29	7
(6) MS-1	2	0	2	2	2	0	2							10	1.43	7
(7) MS-2	1	13	4	4	5	2	5	0	6	4				44	4.40	10
(8) MS-3	0	0	2	0	1	6	4	6	0	0	0	4		23	1.92	12
(9) MS-4	2	0	6	8	4	2	8	0	6	5	6	8	2	57	4.38	13

Table 13-4: Paired Difference in Score Totals by Group

Group (w)	**Student Number in Each Group (v)**													$d_{z_w\cdot}$	$\bar{d}_{z_w\cdot}$	n_w
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**			
(1) HS-1	11	10	2	28	8	10	17	15	29	15	6	13		164	13.67	12
(2) HS-2	4	10	26	23	11	34	0	12	7	12	18	10		167	13.92	12
(3) HS-3	8	2	0	6	11	6	10	10	21	11	6	5	10	106	8.15	13
(4) HS-4	25	13	18	2	20	18	-1	11	16	13	12			147	13.36	11
(5) HS-5	2	16	9	9	26	9	19							90	12.86	7
(6) MS-1	9	8	5	17	8	18	10							75	10.71	7
(7) MS-2	13	37	8	13	14	1	7	8	7	16				124	12.40	10
(8) MS-3	3	11	11	10	8	23	18	12	14	7	10	11		138	11.50	12
(9) MS-4	8	4	9	13	9	10	12	1	6	16	19	9	19	135	10.38	13

Table 13-5: Average of Paired Difference in Element Scores by Instructor

Instruct-or (w)	**Group Number (v)**									$d_{z_w\cdot}$	$\bar{d}_{z_w\cdot}$	n_w
	(1) HS-1	**(2) HS-2**	**(3) HS-3**	**(4) HS-4**	**(5) HS-5**	**(6) MS-1**	**(7) MS-2**	**(8) MS-3**	**(9) MS-4**			
1	6.00									6.00	6.00	1
2		5.67		7.55		6.71		7.75		27.68	6.92	4
3			0.92		6.57		4.50		3.69	15.69	3.92	4

Table 13-6: Average of Paired Difference in Interaction Scores by Instructor

Instruct-or (w)	**Group Number (v)**									$d_{z_w\cdot}$	$\bar{d}_{z_w\cdot}$	n_w
	(1) HS-1	**(2) HS-2**	**(3) HS-3**	**(4) HS-4**	**(5) HS-5**	**(6) MS-1**	**(7) MS-2**	**(8) MS-3**	**(9) MS-4**			
1	3.75									3.75	3.75	1
2		3.83		1.82		2.57		1.83		10.06	2.51	4
3			4.08		4.00		3.50		2.31	13.88	3.47	4

Table 13-7: Average of Paired Difference in Role/Purpose Scores by Instructor

Instructor (*w*)	**Group Number (*v*)**									$d_{z_{w\cdot}}$	$\bar{d}_{z_{w\cdot}}$	n_w
	(1) HS-1	**(2) HS-2**	**(3) HS-3**	**(4) HS-4**	**(5) HS-5**	**(6) MS-1**	**(7) MS-2**	**(8) MS-3**	**(9) MS-4**			
1	3.92									3.92	3.92	1
2		4.42		4.00		1.43		1.92		11.76	2.94	4
3			3.15		2.29		4.40		4.38	14.22	3.56	4

Table 13-8: Average of Paired Difference in Score Totals by Instructor

Instructor (*w*)	**Group Number (*v*)**									$d_{z_{w\cdot}}$	$\bar{d}_{z_{w\cdot}}$	n_w
	(1) HS-1	**(2) HS-2**	**(3) HS-3**	**(4) HS-4**	**(5) HS-5**	**(6) MS-1**	**(7) MS-2**	**(8) MS-3**	**(9) MS-4**			
1	13.67									13.67	13.67	1
2		13.92		13.36		10.71		11.50		49.49	12.37	4
3			8.15		12.86		12.40		10.38	43.80	10.95	4