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CHARACTERIZING HIGH SCHOOL STUDENTS' SYSTEMS THINKING IN  
ENGINEERING DESIGN THROUGH THE FUNCTION-BEHAVIOR-STRUCTURE  
(FBS) FRAMEWORK

by

Matthew D. Lammi

A dissertation submitted in partial fulfillment  
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Education

Approved:

---

Dr. Kurt Becker  
Major Professor

---

Dr. Doug Holton  
Committee Member

---

Dr. Paul Schreuders  
Committee Member

---

Dr. Kay Camperell  
Committee Member

---

Dr. Oenardi Lawanto  
Committee Member

---

Dr. Byron R. Burnham  
Dean of Graduate Studies

UTAH STATE UNIVERSITY  
Logan, Utah

2011

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## ABSTRACT

Characterizing High School Students' Systems Thinking in Engineering Design Through  
the Function-Behavior-Structure (FBS) Framework

by

Matthew D. Lammi, Doctor of Philosophy

Utah State University, 2011

Major Professor: Dr. Kurt Becker  
Department: Engineering and Technology Education

The aim of this research study was to examine high school students' systems thinking when engaged in an engineering design challenge. This study included 12 high school students that were paired into teams of two to work through an engineering design challenge. These dyads were given one hour in their classrooms with access to a computer and engineering sketching paper to complete the design. Immediately following the design challenge, the students participated in a post hoc reflective group interview.

The methodology of this study was informed by and derived from cognitive science's verbal protocol analysis. Multiple forms of data were gathered and triangulated for analysis. These forms included audio and video recordings of the design challenge and the interview, computer tracking, and student-generated sketches. The data were coded using Gero's FBS framework. These coded data were analyzed using descriptive statistics. The transitions were further analyzed using measures of centrality.

Additionally, qualitative analysis techniques were used to understand and interpret systems and engineering design themes and findings.

Through the qualitative and quantitative analyses, it was shown that the students demonstrated thinking in terms of systems. The results imply that systems thinking can be part of a high school engineering curriculum. The students considered and explored multiple interconnected variables, both technical as well as nontechnical in nature. The students showed further systems thinking by optimizing their design through balancing trade-offs of nonlinear interconnected variables. Sketching played an integral part in the students' design process, as it was used to generate, develop, and communicate their designs. Although many of the students recognized their own lack of drawing abilities, they understood the role sketching played in engineering design. Therefore, graphical visualization through sketching is a skill that educators may want to include in their curricula. The qualitative analysis also shed light on analogical reasoning. The students drew from their personal experience in lieu of professional expertise to better understand and expand their designs. Hence, the implication for educators is to aid the students in using their knowledge, experience, and preexisting schemata to work through an engineering design.

(163 pages)

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Matthew D. Lammi

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## CHAPTER I

### INTRODUCTION

In order to maintain a global competitive edge and national prosperity the US needs public literacy in the STEM areas – science, technology, engineering, and mathematics (International Technology and Engineering Education Association, 2000; Pearson & Young, 2002). Education is one of the primary vehicles for advancing a STEM literate populace. However, the education system struggles to define, devise, and improve learning and teaching in STEM education (American Association for the Advancement of Science, 1990; International Technology and Engineering Education Association, 2000; Katehi, Pearson, & Feder, 2009; Schunn, 2008; Wicklein, 2006). Engineering design is a unifying concept and a process that can address this challenge. Design in engineering integrates the STEM disciplines through scientific principles, technological design, and mathematical analysis (AAAS, 1990; International Technology and Engineering Education Association, 2000).

Design is often complex, involving multiple levels of interacting components within a system that may be nested within or connected to other systems. Systems thinking is an essential facet of engineering design cognition (ABET, 2007; Dym, Agogino, Eris, Frey, & Leifer, 2005; Katehi, et al., 2009; Ottino, 2004; Schunn, 2008). Systems thinking may be understood from various perspectives, such as the Structure-Behavior-Function (SBF) framework. The SBF framework associates the system components (structure) to their teleology (function) and the attributes derived from the structure enabling them to perform their functions (behavior). The SBF framework has

been used to understand systems thinking as it “allows effective reasoning about the functional and causal roles played by structural elements in a system by describing a system’s subcomponents, their purpose in the system, and the mechanisms that enable their functions” (Hmelo-Silver, 2004, p. 130). The SBF framework has been successfully used in STEM education. There is more than one SBF framework. SBF is also known as FBS in order to reflect the order of the design process. Additionally, within the FBS framework there are multiple distinct working definitions among authors. Gero’s FBS framework specifically applies to design and is the most thoroughly researched framework.

To better understand and enhance learning and teaching in engineering design, it is invaluable to thoroughly survey and analyze students’ ways of thinking or habits of mind. Engineering design thinking has been researched at the post-secondary level through numerous and diverse studies (Atman, Kilgore, & McKenna, 2008; Dally & Zhang, 1993; Hirsch et al., 2002; Purzer, 2009; Sheppard et al., 2004; Stevens, O’Connor, Garrison, Jocuns, & Amos, 2008). These research studies have ranged from student cognition, service learning, ethnography, mentor programs, to collaboration. Design thinking data has been collected and analyzed using verbal and/or video data (Adams, Turns, & Atman, 2003; Atman & Bursic, 1998; Cross, 2004; Dorst & Cross, 2001; Gero & Kan, 2009; Mosborg et al., 2006). Although researchers have studied engineering design thinking, few researchers have investigated systems thinking. Nor have the studies addressed the impact of engineering design on K-12 students. How K-12 students employ systems thinking processes and strategies within engineering design is not adequately

identified or understood. Hence, there is a need for research in systems engineering design cognition at the K-12 level (Katehi, et al., 2009).

### **Purpose and Objectives**

Cognitive issues are mental activities used during a design challenge while the processes are the way in which the issues are approached explicitly or implicitly. The purpose of this research was to understand the systems cognitive issues and processes used by high school students while engaged in collaborative engineering design challenges. The framework used for cognitive analysis was Function-Behavior-Structure (FBS).

The following objectives helped frame and guide the research in meeting the study purpose:

1. Identify and analyze the systems cognitive issues, within the FBS framework, employed by high school students while engaged in a collaborative engineering design challenge using verbal and video analysis.
2. Identify and analyze the systems cognitive processes employed by high school students while engaged in a collaborative engineering design challenge using measures of centrality.
3. Identify, analyze, and interpret emerging qualitative themes and phenomena as they relate to systems thinking in engineering design.

## Procedures

Through this exploratory triangulation mixed method research, the systems cognitive issues and processes used by high school students while involved in a collaborative engineering design challenge were studied. With the help of their teacher, Wayne Sumner, six teams of two (dyad) students were recruited from an exemplary western regional high school engineering program. The students had taken more than one course in engineering in high school. With the exception of one participant, the students were all seniors or juniors.

Verbal report data were collected to capture the students' cognitive issues and processes (Ericsson & Simon, 1993). The verbal data were augmented with video collection (Derry, 2007) and the tracking of computer movements. The video aided in the analysis when there were instances of non-verbalization. Although a verbal protocol analysis might solicit more verbalization from a single participant, the collaborative verbal interactions that take place between the dyad members are more authentic and are sufficient for collecting verbal and video data (Denson, Lammi, Park, & Dansie, 2010; Kan & Gero, 2009; Purzer, Baker, Roberts, & Krause, 2008). To help capture and clarify the students' deeper understanding and cognition, there was also a post-hoc focus group interview (Zachary, Ryder, & Hicinbothom, 2000). The focus group allowed the researcher to query the students as to their decision making processes. Additionally, the students were asked to provide demographic data including age, gender, and hometown population. Although the design artifacts were not evaluated or assigned a score, they were triangulated with other collected data to further understand the students' cognition.

The design challenge was open-ended, collaborative, complex, and situated in a meaningful context. The students were asked to design a solution to open double hung windows for the physically impaired. The design challenge encompassed engineering, ergonomic, and social constraints. This design challenge has been used by Gero (2010) and colleagues with undergraduate engineering students. Students were familiar with and had access to window knowledge, and, therefore, did not require engineering expertise to successfully work the design challenge.

The audio and video data from the design challenge and the interview were transcribed, segmented, and coded. The data were also coded using the FBS framework (Chandrasekaran & Milne, 1985; Gero, 1990). These coded data were analyzed using descriptive statistics. Each change from one code to the next is a process or transition. These transitions were analyzed by measures of centrality (Lee, Cho, Gay, Davidson, & Ingraffea, 2003; Sosa, Eppinger, & Rowles, 2007). Emergent themes were analyzed qualitatively as they developed (Glesne, 2006).

### **Research Questions**

This research was guided by the following research questions to meet the purpose and objectives of the research. These research questions are numbered below.

1. What are the mental issues, activities, and operations used by high school students when attempting an engineering design challenge analyzed through the FBS framework?

2. What mental processes, approaches, and transitions are present when high school students attempt an engineering design challenge analyzed through the FBS framework?

3. Are there emerging qualitative themes and phenomena as they relate to systems thinking in engineering design? If there are themes or phenomena, how can these themes and phenomena be analyzed and interpreted?

### **Definitions**

*Cognitive issue:* A mental activity or a series of actions and operations.

*Cognitive process:* A linked or sequenced mental approach of cognitive issues.

*Collaborative:* Any activity that involves more than one participant. In this study the collaboration will be face-to-face and does not imply interdisciplinary or distance interaction.

*Descriptive statistics:* Used to describe or summarize a collection of data quantitatively. These analyses typically involve measures of central tendency and dispersion augmented by graphical plots.

*Dyad:* A team of two students working as a team. Not to be confused with a dyad in network analysis, where a dyad is two nodes connected by a link.

*Engineering design challenge:* An educational design activity intended to be authentic and engaging, based on open-ended problems, and performed in collaborative groups. Engineering design incorporates engineering science through analysis, modeling, and prediction.



*Function-Behavior-Structure (FBS):* A framework that attempts to describe the design process through components (structure), teleology (function), and the attributes enabling the function (behavior).

*Link:* The connection between FBS codes used in calculations for measures of centrality.

*Measures of centrality:* The measure of a vertex (node) in a network. This analysis yields the relative importance of a vertex. In this study the FBS codes are the individual vertices.

*Node:* Used in measures of centrality to represent a vertex in a network. In this study, a node represents an FBS code.

*OutDegree:* A measure of centrality used to describe the number of transitions leaving a node or code. This calculation is also based on the number of links to a code.

*Post-hoc focus group:* A focus group of more than one person reflecting on a previous cognitive activity performed and is mediated by a moderator who may ask predetermined or probing questions.

*STEM:* The disciplines of science, technology, engineering, and mathematics.

*STEM education:* The study and educational enterprise of STEM.

*Systems thinking:* A way of thinking that recognizes a system or its components are not isolated from each other or from other systems.

*Transition:* The movement from one FBS code to another or itself. Transitions are used in calculations for measures of centrality.

*Verbal Protocol Analysis (VPA)*: A research method used to collect cognitive processes and strategies from verbal reports.

### **Limitations of the Study**

The limitations in this study are listed below. All research includes biases and limitations (Glesne, 2006). The limitations help define the scope of the research.

1. The student participants only consisted of students from one high school. Therefore, there was discourse and jargon that may be unique to the region and high school program (Atman, et al., 2008).
2. The research only investigated the engineering design cycle to a design proposal. The students did not build, test, evaluate, or revisit their design.
3. Although there are many high school engineering curricula, the students in this study have only been taught using curriculum unique to their high school.

### **Assumptions of the Study**

Assumptions are made for this study as they cannot be ascertained empirically. Additionally, the study identifies these assumptions to maximize validity and trustworthiness.

1. The high school students had comparable engineering training. They had taken more than one course in pre-engineering.
2. The students were primarily in their senior or junior years and selected by their engineering instructor.

3. Students were honest and open in approaching the design challenge and in the post hoc interview.

4. The researcher administered the research with all the participants in a similar fashion.

## CHAPTER II

### REVIEW OF LITERATURE

#### **Defining STEM Education**

Although the acronym STEM (science, technology, engineering, and mathematics) is relatively recent, the respective educational disciplines have existed for centuries and for the most part, independently. The idea of STEM as a united educational entity is rare if non-existent in practice (Sanders, 2009). Nevertheless, STEM education can and should be addressed holistically and not individually (Katehi, et al., 2009). In professional practice STEM is widely overlapping and is not performed in isolation. Engineering design is no exception. Both engineering and technology claim design as their hallmarks. Engineering design relies upon the principles of science, employs analytical analysis through mathematics, and exploits the human-made world of technology to answer problems or realize needs and opportunities.

#### **Need for STEM Education**

The flight of Sputnik in 1957 was far more than the successful test of a transmission satellite. The impact reached beyond the borders of the Soviet Union and extended deep into the United States (US). The US responded with unprecedented funding for defense, aerospace, science, and their related educational fields, as manifested in the National Defense Education Act of 1958. Integrated STEM education in K-12 was poised for success. However, educational disciplines maintained the status

quo. Now, over 50 years later, the US faces a similar educational challenge. The challenge is to overcome the decline of student performance in STEM education, diminished national STEM literacy, and the lack of a rising workforce in the STEM disciplines (National Academy of Engineering, 2004). Whether or not STEM education becomes more than a buzzword, to a large extent depends upon the understanding and the integration of STEM educational disciplines.

### **Study Selection Criteria**

Engineering design as the essence of engineering and as a pedagogical tool has captured the attention of literature in the STEM areas and education disciplines (Atman & Bursic, 1998; Brophy, Klein, Portsmouth, & Rogers, 2008; Brown, 2001; Katehi, et al., 2009; Lewis, 2004; Mehalik & Schunn, 2006; Schunn, 2008; Wulf & Fisher, 2002). The body of literature in systems thinking within STEM has increased in the past few years. One of the measures, or theoretical framework, of systems thinking has been FBS. From the National Research Council Press to journals such as *The Journal of Engineering Education*, *The Technology and Engineering Teacher*, *Design Studies*, and the *Journal of the Learning Sciences*, there is evidence of a heightened interest in systems thinking in the STEM areas.

The following key words or their combinations were used to obtain this body of literature: engineering design, k-12, engineering education, design challenge, STEM, FBS, systems thinking, complexity, technology design, verbal protocol, and cognitive theory. In addition to the journals listed above, the following databases were searched:

Science Direct, Google Scholar, ACM Portal, and IEEE Xplore. The literature selected for the integrative review had to meet the following criteria: (a) be peer reviewed; (b) and address STEM disciplines or design. The literature was coded for: (a) engineering design; (b) STEM design challenge; (c) systems thinking; (d) FBS; (e) verbal protocol; (f) video; (g) interview; (h) collaborative. There were 52 articles used; see Table 1.

Table 1

*Integrative Literature Review Results*

Author/Year	Engr Dsgn	STEM Dsgn Chlng	System	FBS	Verbal Data	Video	Inter view	Collaborative
Adams et al., 2003	X	X			X			
Atman & Bursic, 1998	X	X			X			
Atman et al., 2008	X	X			X		X	
Atman et al., 1999	X	X			X	X		
Atman et al., 2007	X	X			X			
Baird et al., 2000	X	X	X					X
Brophy, 2008	X	X	X	X				
Bucciarelli, 1988	X							X
Chandrasekaran & Milne, 1985			X	X				
Charles & d'Apollonia, 2003		X	X				X	X
Cross, 1994		X			X			
Cross, 2002	X	X			X		X	
Cross, 2004	X				X			
Dally & Zhang, 1993	X	X						X
Dorst & Cross, 2001	X	X			X			
Doyle, 1997	X		X					
Ennis & Gyeszly, 1991	X	X			X			
Foster et al., 2001	X		X					X
Gero & Kan, 2009	X	X		X	X	X		X
Gero & Kannengiesser, 2002				X				
Gero & Lindemann, 2005				X				
Goel, 1997	X		X	X				

*(table continues)*

Author/Year	Engr Dsgn	STEM Dsgn Chlng	System	FBS	Verbal Data	Video	Inter view	Collaborative
Goldstone & Sakamoto, 2003			X					
Guindon, 1990	X	X			X			
Hirsch, 2002	X	X						X
Hirsch, 2003	X	X						X
Hmelo et al., 2000	X	X	X	X			X	X
Hmelo-Silver & Azevedo, 2006			X	X				
Hmelo-Silver & Pfeffer, 2004		X	X	X	X		X	
Jacobson & Wilensky, 2006	X	X	X					X
Jagodzinski et al., 2000	X		X					X
Kan & Gero, 2008			X					
Kan & Gero, 2010	X	X		X	X	X		X
Kavakli & Gero, 2002					X	X		
Kittleson & Southerland, 2004	X							X
Lehrer, Schauble, & Lucas, 2008			X					
Lehrer & Schauble, 1998		X						
Lehrer & Schauble, 2000		X						
McKenna, 2005	X							
McMartin, 2000	X	X						
Mehalik et al., 2008	X	X	X					
Morozov, 2008	X	X						
Mosborg, 2005	X	X			X			
Mullins, Atman, & Shuman, 1999	X	X			X			
Purzer, Baker, Roberts, & Krause, 2008a	X	X				X		X
Purzer et al., 2008b	X	X			X	X		X
Sabelli, 2006			X					
Schunn, 2008	X	X	X	X				
Sheppard, 2004	X	X						
Stevens, 2008	X							
Svensson & Ingerman, 2009			X	X			X	
Sweeney & Serman, 2000		X	X					

## Engineering Design

Engineering design can serve as an integrator for STEM education. Thirty-five of the 52 articles addressed the need and benefit of engineering design in STEM. Both technology education and engineering education use design as a pedagogical activity with similarities between the two design processes (Hailey, Erekson, Becker, & Thomas, 2005). Furthermore, engineering design applies scientific and mathematic principles to bring about technology used by humankind. ABET (2007) defined engineering design as

...the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs. (p. 3)

Engineering design is more than the mere manipulation of numbers and the solving of scientific equations. The processes employed in engineering design encompass a broad variety of topics and fields of study. Design is dynamic and iterative, therefore, it is not easily represented by simplistic linear models (Mawson, 2003). Jonassen (2000) places design in a distinct type in his “problem type taxonomy.” Design is not only listed as complex and ill-structured, but it also requires higher order problem solving skills.

There are diverse models of design varying in complexity and scope (Cross, 2004; Dym, et al., 2005; Eide, Jenison, Mashaw, & Northrup, 2002; Gero & Kannengiesser, 2004; Hailey, et al., 2005; International Technology and Engineering Education Association, 2000; Schön, 1983). One simple perspective asserts that design has a problem and a solution space. Design typically commences with defining the problem space (Schön, 1983). The purpose of defining the problem space is to gather pertinent data, delineate the overall goal, and create an initial plan or “next steps.” The designer



then moves from the problem space to the solution space (Cross, 2004). However, the process may move between the problem and solution spaces iteratively as new insights or constraints are gained. Engineering design typically entails the resolution (trade-off) of the designer's goal, natural and physical laws, and the criteria set forth by clients or other external parties (Cross, 2002). The external criteria are often constrained and associated with resources, such as capital or time (Dym, et al., 2005).

Jonassen and Tessmer (1996) further asserts that as a problem type, design skills are influenced by domain knowledge, cognitive skills, and affective traits. This is supported by Ericsson (2001) who stated that the affective traits, focus, and commitment are also factors in design. Through the lens of an ethnographer, Bucciarelli (1988, 1994) described engineering design as a social process. The National Academy of Engineering clearly stated that engineering education was deficient if it did not include the global perspective in engineering design such as social, political, and environmental issues (NAE, 2004, 2005). The global perspective of engineering involves viewing design from the whole systems level rather than from an isolated modular perspective.

### **Design Challenges**

Engineering design may be expressed and carried out through various approaches. One of these approaches is the design challenge. Of the 52 articles reviewed, 33 included design challenges in the research. Design challenges are intended to be authentic and engaging, based on open-ended problems, and performed in collaborative groups (Dym, et al., 2005; Prince, 2004; Schunn, 2008). An ideal engineering design challenge would

encompass the complete engineering design process; however, an engineering design challenge may only incorporate a few facets of the complete design process for pedagogical feasibility (Adams, et al., 2003; Atman, Chimka, Bursic, & Nachtmann, 1999; Dally & Zhang, 1993; Katehi, et al., 2009).

Design challenges have been widely used in education and research (Atman & Bursic, 1998; Atman, et al., 2008; Cross, 2002; Cross, Christiaans, & Dorst, 1994; Dally & Zhang, 1993; Hadim & Esche, 2002; Hmelo-Silver, 2004; Mehalik, Doppelt, & Schunn, 2008). Design challenges are used in formal academic settings as well as informal settings such as robotics, solar powered vehicles, and rocketry. Design challenges are also used in service learning (O'Neil & Lima, 2003). Although it may be argued that engineering underclassmen are not capable of engineering design, research has shown that these students may succeed with appropriate scaffolding (Dally & Zhang, 1993; Dym, et al., 2005; Lammi & Belliston, 2008). Hirsch et al. (2002) also found that freshman engineering students were capable of design, particularly when assisted by a mentor. Schema theory supports design for underclassmen contending that students come to the table with experience and knowledge and are not blank slates (Bruning, 1999). John Dewey (1897) further concurred, maintaining that students are not empty vessels into which teachers may pour their abundance of knowledge. Design challenges are currently used effectively in engineering education research and practice.

There are numerous engineering design challenges that may be used in engineering education. Clearly, not all engineering design challenges are appropriate for every situation. Design challenges vary in duration such as a two semester long capstone

project or a 15-minute street crossing problem to gauge students' approach to the design process (Atman, et al., 2008). The appropriate design challenge must also fit the research question. To help understand systems thinking, the challenge should exploit a system such as the human lungs, an aquarium, or an alarm network (Hmelo-Silver, Holton, & Kolodner, 2000; Hmelo-Silver & Pfeffer, 2004; Mehalik, et al., 2008).

**Engineering design in STEM.** Design challenges are also used outside of engineering curricula (Mehalik, et al., 2008; Schunn, 2008). Hmelo-Silver et al. (2000) employed a design challenge in a sixth-grade science classroom. The students were to design, build, and test artificial human lungs. The aforementioned authors offered suggestions for implementing engineering design into core curricula. The authors posited that the engineering design process is novel to most educators outside of engineering. Therefore, if an educator is to implement new engineering content, it is suggested that she or he have a minimum level of competency in teaching and delivering the engineering design process first. Additionally, "the teachers [with whom they had been working] prefer to introduce students to design and modeling practices early in the school year in a way that doesn't require deep learning of science content at the same time" (Hmelo-Silver, et al., 2000, p. 292). The authors also suggest that students may begin the design process without thorough background knowledge as "there is always something they can get started with based on what they already know" (Hmelo-Silver, et al., 2000, p. 288). Another finding worth noting is the informal collaboration between groups. The students were able to critique and glean from other teams' creativity and work. Although in industry engineers are generally not privy to their competitors' proprietary designs, it is

“good practice” to collaborate with other teams and departments within the same company. The authors coined this collaborative activity “gallery walks.”

### **Complexity and Systems Thinking in Engineering Design**

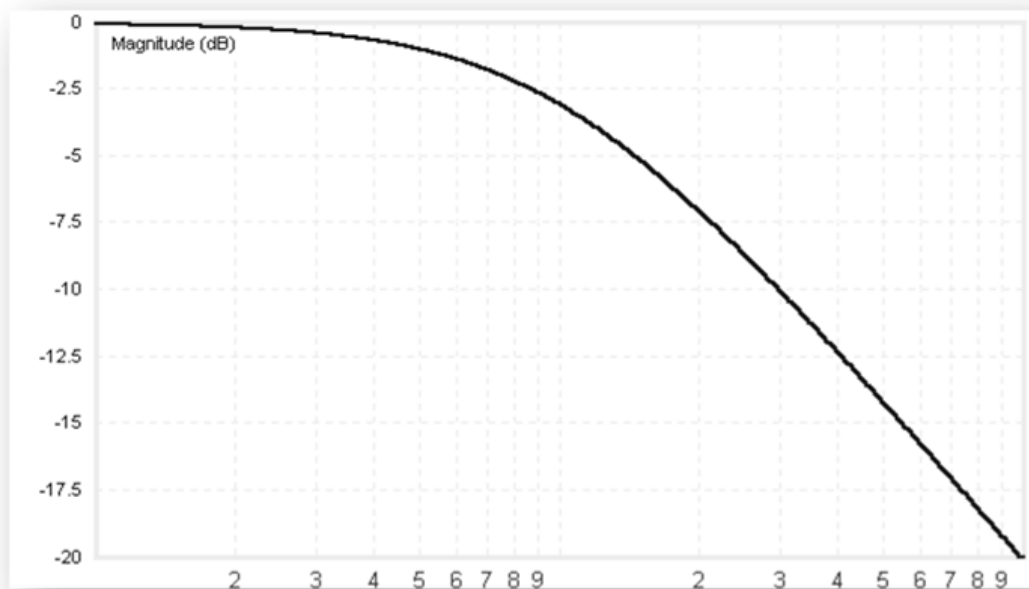
This section will explore the literature on complexity and systems thinking as it relates to engineering design. Engineering is moving from immediate problems such as structural integrity to broader interconnected issues of environmental impact, political implications, and aesthetics (Foster, Kay, & Roe, 2001). Twenty-three articles from the integrative review addressed the importance of systems thinking in STEM. The National Academies have echoed similar sentiments regarding engineering (NAE, 2005). In the nascency of science education as a formal subject in US public schools, John Dewey (1916) stated that the curriculum should “arouse interest in the discovery of causes, dynamic processes, [and] operating forces.”

**Complexity.** As the name suggests, complex systems are not easily defined and have given way to various precepts and constructs. Sweeney and Sterman (2000) assert that,

There are as many lists of systems thinking skills as there are schools of systems thinking... [yet] most advocates of systems thinking agree that much of the art of systems thinking involves the ability to represent and assess dynamic complexity. (p. 250)

Davis and Sumara (2006) further concurred that complex systems are dynamic and adaptive. Systems are dynamic with respect to time, and these distinct variables may differ along unique time scales. Complex systems have multiple interconnected variables with emerging interactions that cannot be viewed in isolation in order to understand the

aggregate system (Hmelo-Silver & Azavedo, 2006). Complexity in systems is generally non-linear and unbounded (Davis & Sumara, 2006; Foster, et al., 2001). Most physical and social phenomena at the systems level do not follow a simple cause-effect relationship. Figure 1 displays the nonlinearity of a simple electronic circuit that does not follow linear causes and effects. Schuun (2008) also defined optimization in complexity



*Figure 1.* Frequency response of a simple filter circuit. The Y-axis is in dB and the X-axis is a logarithmic scale starting at .1 Hz. Although there is a linear portion of the graph above 1 Hz, the lower frequencies are nonlinear.

as balancing constraints, trade-offs, and requirements. In summary, complex systems are dynamic, adaptive, emergent, non-linear, and iterative. These systems are also influenced by multiple time scales, contain interconnected variables, and often include humans as another variable.

A practical example of a complex engineering system is the frequency design of a wireless radio frequency (RF) cellular phone network. An RF engineer is constrained by time, resources, and a limited number of frequencies (channels) for a vast system. Multiple factors influence an engineering design, such as the signal simulation software. Electromagnetic signals are continuous in all directions, yet in the simulation software the signal representation is blatantly discrete assuming the terrain is the same for 100 meter bins. Higher resolution can be achieved at a higher financial price, but the analysis is exponentially longer in duration. Another factor is the electromagnetic propagation through vegetation. As seasons change, so does the cellular phone coverage. RF engineers can only obtain a snapshot of the system at one point in time. Perhaps the most widely varying factor is the cellular phone traffic usage. The traffic may vary cyclically or anomalously due to perturbations such as traffic accidents, catastrophes, and sporting events. This paper is not exhaustive and will not delve into the myriad variables that influence RF frequency design. Suffice it to say, RF systems engineering design is a highly complex and dynamic endeavor.

### **Facets of Complexity and Systems in Engineering Design**

**Multiple interconnected variables.** Many of the facets of complexity science are found in engineering design. Engineering design encompasses multiple interconnected variables. In addition to the technical variables, such as temperature, load, or electrical current, there are non-technical variables as well. Wulf and Fisher (2002) offered a few possible non-technical variables encountered in engineering design: concerns for safety,

environmental impact, ergonomics, nature, cost, reliability, manufacturability, and maintainability. It is also worth noting that this class of problems also includes human variables (Brophy et al., 2008; NAE, 2004, 2005). In an engineering problem, the designer has to decide which variables are germane and which are not. Furthermore, the relevant variables might also be analyzed for interactions. Engineering designers must often consider interconnected, wide-ranging, and non-linear variables.

Interconnected variables may be complicated and they may be complex. Complicated systems are elaborate and have multiple variables. Complex systems may be complicated, but they may also have variables that interact non-linearly and yield emergent properties. Furthermore, engineering design is a complex process in itself.

**Open-ended.** Jonassen (2000) describes design as a form of problem solving that is open-ended and complex. Engineering designs generally have multiple solutions and varying solution paths (Brophy, et al., 2008; Eide, et al., 2002; Foster, et al., 2001). There is not typically one right answer. Although distinct designs might approach convergence, the process of arriving at the final design could have been sought through drastically unique paths. Ottino (2004, p. 399) stated, “Most design processes are far from linear, with multiple decision points and ideas evolving before the final design emerges.”

**Emergence.** In addition to containing multiple variables, the variables often vary non-linearly along unique time scales. An example would be an aerospace launch vehicle with multiple stages. The launch vehicle will experience dynamic temperatures, pressures, and gravitational effects while traveling through distinct settings in the

atmosphere into space. The behaviors resulting from the interaction of components in a system is termed emergence in engineering design (Katehi, et al., 2009). Katehi et al. (2009, p. 125) further stated, “Aggregate behavior is qualitatively distinct from the sum of behaviors of individual components and indicates a complex engineered system, such as highways, the Internet, the power grid, and many others, which are all around us.” Other examples of complex systems include transportation, the Internet, and the physical locations of companies in a city.

### **Systems Processes within Engineering Design**

**Optimization.** Engineering requires that the designer meet multiple, possibly conflicting, requirements or constraints through optimization (Brophy, et al., 2008; Cross, 2002; Katehi, et al., 2009; Silk & Schunn, 2008). Optimization is generally an iterative process that balances trade-offs. These trade-offs may include the competition of performance versus cost, robustness versus social constraints, and time versus environmental impacts. Although the components in trade-offs may be considered individually to help understand the system, the components often interact with each other, thus, cannot be evaluated independently. Iteration is an integral component of optimization and may occur at any point in the design process (Hailey, et al., 2005). Iteration may be understood as the process of revisiting a design with the intent of improvement while balancing constraints. Although optimizing trade-offs may impose a substantial cognitive load, the concept of trade-offs can be learned through improved



pedagogical and curricular strategies. These strategies include mathematical modeling and iteration (Silk & Schunn, 2008).

**Sketching.** Katehi et al. (2009) suggested sketching can help students improve systems thinking. Sketching can be used for representation and generation of ideas (MacDonald, Gustafson, & Gentilini, 2007). Research suggests that the role of representation dominates the role of idea generation in classrooms (Anning, 1997; Garner, 1992; MacDonald, et al., 2007). Garner claims that most drawings are not seen by others; rather the drawings aid the designer in ideation and idea development. Anning (1997, p. 237) stated, “Drawing and the processes by which they are made give us a window on children’s cognitive processing which can be as informative as studying their language.” Sketching can reduce the designer’s cognitive load, “The sketch serves as a cognitive support tool during the design process; it compensates for human short-term memory limitations and at the same time supplements cognitive effort by depicting the mental imagery in a concrete form” (Plimmer & Apperley, 2002, p. 9).

### **Complex Systems in Engineering Education Rationale**

Dym et al. (2005) unambiguously stated that design thinking is complex and offer the following definition of engineering design:

Engineering design is a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients’ objectives or users’ needs while satisfying a specified set of constraints. (p. 104)

Dym et al. (2005, p. 106) further stated, “A hallmark of good systems designers is that they can anticipate the unintended consequences emerging from interactions among

multiple parts of a system.” The American Society for Engineering Education’s seminal report in the 1950s on engineering education, commonly referred to as the Grinter Report, advocates as one of their primary tenets “an integrated study of engineering analysis, design, and engineering systems” (Grinter, 1956, p. 74) The national organizations ABET and the National Academy of Engineering (NAE) both promote systems thinking for engineers. ABET (2007, p. 3) defined engineering design as follows, “Engineering design is the process of devising a *system*, component, or process to meet desired needs.” As mentioned previously, NAE (2005) called for the next generation of engineers to be global, or systems, in their thinking and practice. Support for systems thinking in engineering comes from researchers, practitioners, and preeminent national organizations alike.

Systems thinking is the ability to understand the components of a system and how they interact as well. Katehi and colleagues (2009, pp. 5, 91) explained that a system “is any organized collection of discrete elements designed to work together in interdependent ways to fulfill one or more functions” and that systems thinking “equips students to recognize essential interconnections in the technological world and to appreciate that systems may have unexpected effects that cannot be predicted from the behavior of individual systems.”

Not all engineering requires systems thinking for not all engineering problems are complex. Structured problems and Newtonian principles are not only present in engineering practice but are also helpful in engineering education pedagogy and content.

Furthermore, complex problems may be broken down into subsystems for a more simple understanding (Schunn, 2008).

### Function-Behavior-Structure

Function-Behavior-Structure (FBS) is a framework for representing a design process. As design often involves systems or components that are part of a system, the FBS framework is used to elucidate systems thinking. Twelve articles from the integrative review advocated and/or used the FBS framework. Systems can be either natural or human-made. Gero and Kannengiesser (2004) offered a definition and conceptualization, Figure 2, of FBS.

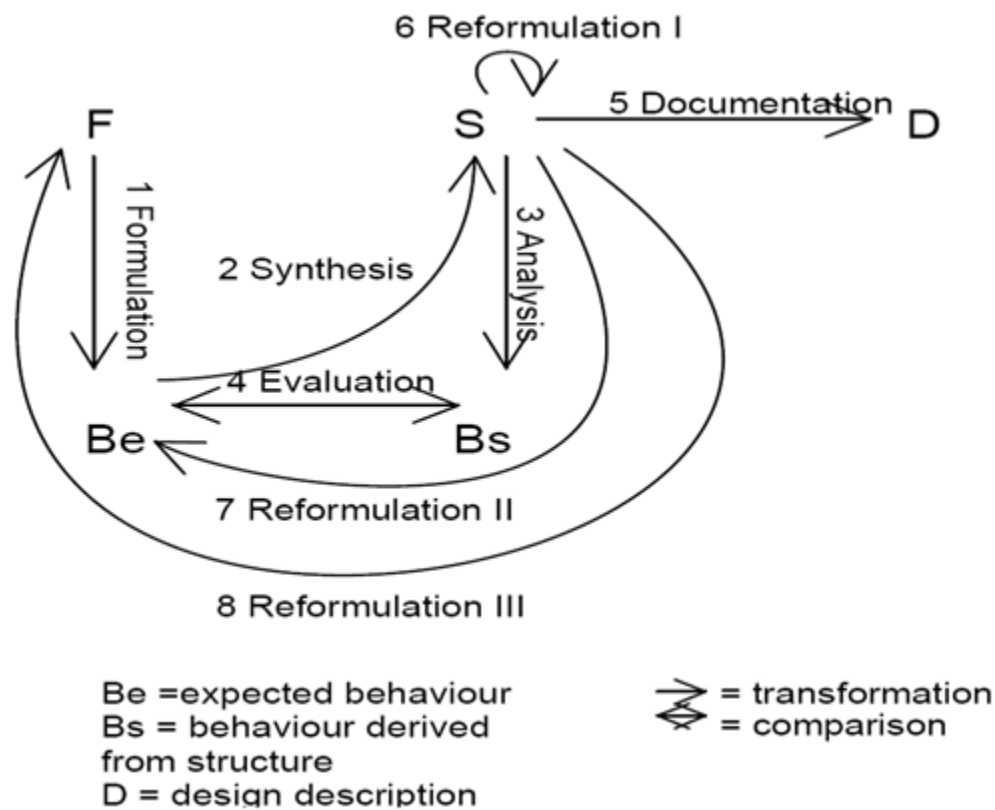


Figure 2. Gero's Function-Behavior-Structure framework (Gero & Kannengiesser, 2004).

1. Function variables describe the teleology of the object, i.e. what it is for
2. Behaviour variables describe the attributes that are derived or expected to be derived from the structure variables of the object, i.e. what it does.
3. Structure variables describe the components of the object and their relationship, i.e. what it is. (p. 374).

Kathehi et al. (2009, p. 123) proffered another definition: “FBS relates the components (structures) in a system to their purpose (function) in the system and the mechanisms that enable them to perform their functions (behavior).” Katehi et al. (2009, p. 91) further stated that the FBS framework is well suited for describing systems thinking this way: “Systems thinking involves identifying parts [Structures], determining their function [Function], uncovering relationships, discovering how they work together as a system [Behavior], and identifying ways to improve their performance.”

FBS was first introduced by Chandrasekaran and Milne (1985) in artificial intelligence (AI) design. Gero (1990) further developed the FBS framework in AI. Recently, Gero has applied the FBS framework to engineering students and software developers. Other researchers have expanded the FBS framework to the K-12 arena to understand cognition within complex systems (Goel, 1997; Hmelo-Silver, 2004; Hmelo-Silver, et al., 2000). “The SBF framework allows effective reasoning about the functional and causal roles played by structural elements in a system by describing a system’s subcomponents, their purpose in the system, and the mechanisms that enable their functions” (Hmelo-Silver, 2004, p. 130). FBS is not a complete theory for describing the

design of systems, but rather a framework that aids in the understanding of human cognition in complex systems.

### **Verbal Protocol Analysis**

In their seminal work on verbal protocols, Ericsson and Simon established verbal reports as data (1980). Ericsson and Simon also explained how the reports are generated and how they are sensitive to experimental factors such as instructions and tasks.

Therefore, there should be minimal interference from the experimenter. Verbal protocol analysis (VPA) is a method for collecting verbalization of the participants thinking out loud as they attempt to solve a task or problem. An audio and/or video recording is made in order to capture the participants thought processes. The text is transcribed for data analysis. These data may then be organized, segmented, and coded. The coding may be performed according to an established scheme (Atman, et al., 1999; Kan & Gero, 2009; Mosborg, et al., 2006) or as new themes and phenomena develop (Cross, 2002; Ennis & Gyeszly, 1991; Purzer, 2009). The final step is to analyze the data to answer research questions (Chi, 1997). Although Hayes (1989) conceded that verbal protocols are typically incomplete for capturing all cognition, he also claims that under controlled conditions there is no evidence that verbal protocols detrimentally distort or interfere with the participant's thinking while engaged in a task or solving a problem.

Hayes also asserted that a VPA is a description of an activity ordered in time (1989). Hayes (1989) further stated:

When we collect protocols of people solving problems, we are not just interested in the answers they give us, but, more importantly, in the sequence of things they

do to get those answers. They do things – such as draw diagrams, make computations, and ask questions – in a particular order. (p. 70)

Therefore, the sequence of activities or events is important for verbal reports. Gero and his colleagues have investigated sequences of verbal reports by analyzing the links between coded segments (Gero & Lindemann, 2005) and when certain processes occur (Gero & Kan, 2009).

Design has been studied using verbal protocol analysis even as early as the late 1970s (Simon & Simon, 1979). However, the study of design in engineering and technology using VPA began in earnest in the 1990s with Atman and her colleagues (Atman & Bursic, 1998). There were 17 articles from the integrative review where verbal protocol was employed to collect and analyze data.

### **Expert-novice in VPA**

Human thinking or cognition has been analyzed using various techniques and protocols. One of the frameworks for analyzing cognition is the expert-novice continuum (Dreyfus, 1987). Generally, the first stage of design is to frame the problem (Cross, 2004). Novice designers tend to dwell in this phase due to their lack of design skills (Cross, et al., 1994). Problem framing yields the identification of constraints, trade-offs, and other variables within a design as well as the overall scope of work. Whereas novices spend considerable time in the problem space, research suggests that experts spend the majority of their time in the solution space (Lawson & Dorst, 2005). Furthermore, experts can recognize what is germane in the problem space and move quickly to the solution space. However, experts iteratively go between both solution and problem spaces (Dorst

& Cross, 2001). Experts also draw heavily from experiential and episodic memory (Cross, 2004). Cross (2002) described how experts in design relied on “first principles” within their domain, or the idea that form follows function. Domain knowledge and experience is the foundation upon which expertise is built. There is a clear difference between expert and novice designers. Experts rely heavily on experience and first principles, quickly capture relevant constraints and variables, and are solution-oriented.

### **Summary and Recommendations**

Engineering design could potentially benefit a diverse group of students whether or not they pursue engineering as a career. As engineering design challenges are vehicles that employ the engineering design process, they have the potential to reveal rich information regarding students’ design thinking. Verbal and video data are well suited to capture cognitive processes and strategies, albeit not exhaustively. Engineers often work with systems and complex problems, whether technically or socially oriented. One framework used for analyzing complex systems is FBS. The FBS framework helps explain how well the student understands not only the surface level characteristics, but the meaning and purpose behind the system as well. As researchers begin to better understand how students use systems thinking, the more informed engineering design education can be. This review of literature suggests that more research is needed to further understand student systems cognitive processes and strategies in engineering design. A viable approach to analyzing cognition of a complex process such as engineering design is through the framework of FBS. FBS has the potential to identify

where student cognitive deficiencies may persist and offer an effective systems approach to engineering design.



## CHAPTER III

### METHODOLOGY

Engineering design thinking is a topic of interest to STEM practitioners and researchers alike (Atman, et al., 2008; Dally & Zhang, 1993; Hirsch, et al., 2002; Purzer, 2009; Sheppard, et al., 2004; Stevens, et al., 2008). Engineering design thinking is “a complex cognitive process” including divergence-convergence, a systems outlook, ambiguity, and collaboration (Dym, et al., 2005, p. 104). One facet of engineering design is systems thinking. Although systems thinking has not previously played a prominent role in engineering education research, it was addressed and emphasized frequently in the NAE’s recent book, *Engineering in K-12 Education* (Katehi, et al., 2009). Due to the nascency of systems thinking in engineering education there are few studies that have investigated systems thinking and its impact in engineering design for K-12 students. Therefore, how high school students employ systems thinking processes and strategies is not adequately understood or identified. Hence, there is a need for research in systems thinking within engineering design at the K-12 level (Katehi, et al., 2009).

This triangulation mixed method research sought to understand the systems cognitive issues and processes used by high school students in a collaborative engineering design challenge. Cognitive issues are the mental activities during the design challenge while the processes are how the issues are approached explicitly or implicitly. The high school students were paired into dyads while attempting a window design challenge. The students had taken more than one high school engineering course. Verbal reports, as well as video were collected to capture the students’ cognitive processes and

strategies (Ericsson & Simon, 1993). There were post-hoc focus group reflective interviews following the challenge (Zachary, et al., 2000). The audio and video data from the design challenge and interview were transcribed, segmented, and coded. Additionally, software tracked the students' activity on a desktop computer. The data were coded using the FBS framework (Chandrasekaran & Milne, 1985; Gero & Kan, 2009). Qualitative and quantitative methods were used for data analysis. These coded data were quantitatively analyzed using descriptive techniques. Furthermore, the processes as transition were analyzed descriptively as well as by measures of centrality (Lee, et al., 2003; Sosa, et al., 2007).

### **Research Questions**

This research was guided by the following research questions to meet the purpose and objectives of the research. These research questions are numbered below.

1. What are the mental issues, activities, and operations used by high school students when attempting an engineering design challenge analyzed through the FBS framework?
2. What mental processes, approaches, and transitions are present when high school students attempt an engineering design challenge analyzed through the FBS framework?
3. Are there emerging qualitative themes and phenomena as they relate to systems thinking in engineering design? If there are themes or phenomena, how can these themes and phenomena be analyzed and interpreted?

## Participants

This study included 12 student participants (working in teams of two) drawn from a high school offering exemplary engineering experiences. “In comparison to quantitative studies, with their emphasis on large, representative samples, qualitative research focuses on smaller groups [samples] in order to examine a particular context in great detail” (Borrego, Douglas, & Amelink, 2009, p. 57). The students worked in pairs for the design challenge. Therefore, there were six dyads. There were tradeoffs to consider when choosing a team size. Larger teams bring more diversity and possibly more divergence to the team (Rau & Heyl, 1990). Kan and Gero (2009) found that while there were seven participants in the team, the conversation was dynamically dominated by two persons. Gokhale (1995) concurred asserting that large team sizes do not facilitate the participation of all team members. The number of participants in mixed methods studies investigating cognition in STEM have varied from two, seven, 19, to over 300 with a median around 10 participants (Atman et al., 2007; Kavakli & Gero, 2002; McMartin, McKenna, & Youseffi, 2000; Purzer, 2009; Sheppard, et al., 2004). This study paired students in a dyad to maximize verbalization of the participants.

### Participant and School Selection

**School selection.** A high school engineering program was chosen that had open-ended authentic engineering design as part of the curriculum. Authentic is defined as a challenge that is similar to what is experienced in industry: open-ended, realistic constraints, collaborative, and includes an artifact or artifact design. The high school

program was chosen through chain sampling (Glesne, 2006). Chain sampling for this research involved asking those “in the know” (teacher educators, graduate students as practitioners, the state office of education) to recommend high school programs. The school was chosen from the surrounding Northern Mountain West Region. From the recommendations, the school program chosen was Northridge High School in Layton, Utah.

Northridge High School is in the Davis School District and has approximately 2,000 students. There are 80% Whites, 10% Latino, 3% Asian, 2% Black, 1% Native American, and 4% unknown (Public School Review, 2010). The school has a certified pre-engineering program using Project Lead the Way curriculum. There are six courses offered that become available to the students starting their sophomore year: Introduction to Engineering, Digital Electronics, Civil and Architectural Engineering, Computer Integration and Manufacturing, Principles of Engineering, and Engineering Design and Development. The engineering instructors have to be certified in each course to be able to teach it. The upper classmen instructor was a retired mechanical engineer who had worked for large and small companies.

**Participant selection.** The participants were chosen through purposeful sampling (Gall, Gall, & Borg, 2007). This sampling method allowed for the development of insights into the characteristics of the engineering students. As engineering courses are elective in this region, the students had taken more than one course by choice. The engineering high school students were recruited with assistance from their high school engineering instructor. Following the morning announcements, the instructor informed

the students of the opportunity of participating in this research. The instructor began recruitment with the senior level design course and then opened up the study to juniors. Students with the highest number of engineering courses were given priority. The majority of the students selected for this study were upper classmen. Additionally, students were selected for interest and availability as this study was performed during non-school hours. The students were given copies of the informed consent with the instruction to bring one signed copy to the design challenge to be collected by the researcher. The students were randomly paired from the pool of available students. The students received a \$10 honorarium and an additional \$30 was donated to their engineering program. The money given to the engineering program helped with new equipment, materials, and class fees for low socioeconomic students.

### **Institutional Review Board**

This study received an IRB approval from USU, #2555 (Appendix A). The study took place at the respective school facility with the assistance from the engineering and technology teacher. Letters of consent for the participating students and their parents were also obtained (Appendix B). Letters of approval were received from the school district and school principal (Appendix C). The students were informed that they were able to withdraw from the experience at any time without any repercussions. The participants were also assured that no part of this research would be included in their academic grades.

Each student dyad was assigned a dyad ID number. Each data collection was associated with that generated ID number. A coding sheet associating ID number with student names was kept separately and locked in a filing cabinet in the researcher's office. Only the researcher had access to this coding document. After data were collected and analyzed, the document which connects student names and ID numbers was destroyed.

## **Data Collection**

### **Overview**

Qualitative and quantitative data were collected simultaneously. Conducting the design challenge at the respective high school accommodated the study participants. The participants attempted the design challenge in a classroom with minimal distractions. The data collection took place outside of the regular school hours, such as after school or on the weekend. Furthermore, the room was arranged to collect audio, video, and computer software movements (keystrokes, web pages visited, and internet searches). Students worked in dyads to approach the design challenge. The demographic questionnaire (Appendix D), the window design challenge (Appendix E), and the post-hoc focus group interview (Appendix F) were collected for each dyad. The data were transcribed, coded, and analyzed following the data collection.

## **Instrumentation**

The participants filled out an anonymous demographic questionnaire prior to the design challenge. The questionnaire included: age, gender, ethnicity, year in school, community description, highest education level of father, mother or guardian(s), and the number of engineering courses taken in high school. The students were also given an orientation to the research protocol. Audio and video were recorded during their participation in the engineering design challenge. Additionally, the students produced a design artifact, sketches, from the design challenge which was included in the analysis. The artifact was not evaluated, but rather used as another source for data corroboration. A post-hoc semi structured interview was conducted following the design challenge. The questions were adapted and derived from previous research on engineering design (Atman, et al., 2008; Cross, 2002; Hmelo-Silver, 2004). There was also software tracking data, Spector® Pro 2010 (version 7.0.5458, Spectorsoft, Vero Beach, FL) which followed and collected the students' movements while on the computer.

## **Research Setting**

This research sought to gather students' systems cognitive processes and strategies. Therefore, the research data were collected in an in-vitro (laboratory) environment to reduce the amount of confounds for this emerging research. Many verbal protocol studies are performed in a controlled environment (Adams, et al., 2003; Atman, et al., 2008; Dorst & Cross, 2001; Gero & Kan, 2009). The distractions inherent in an authentic setting, such as phones, emails, and other humans can distract the participant's

cognition on the task. The participating students received a packet from their high school instructor with copies of the informed consent and contact information. The design room had a video and two audio devices in the form of a camcorder and digital voice recorder respectively.

Each student was paired with another student to perform the design challenge. The students had access to materials to aid in their design such as a desktop computer with internet access, engineering graphing paper, and pencils. Similar to Atman and Bursic's (1998) work, the students were given a time frame to complete the design proposal; they were given one hour. This time frame was derived from Gero's previous work with design challenges (Gero & Kan, 2009; Gero & McNeill, 1998; Kan & Gero, 2010).

### **Engineering Design Challenge**

The window design challenge has been used by Gero and colleagues with undergraduate engineering students. The window design was chosen because it can be attempted by participants without specific engineering training. Additionally, the design encompasses a variety of constraints. The variables are technical, ergonomic, and social. The challenge is only complete if the students submit a design proposal. The design proposal was not specific in how it was to be submitted. The students used the resources available to them: paper and/or computer software. However, the entire design process was not evaluated because the proposal was not built and tested. Appendix E contains the design brief given to the students. The design brief was distinct from that used in other



engineering design thinking studies, as the participants were not engineers. Therefore, the participants were asked specifically to produce an engineering design and analysis to provide an engineering context.

While working in teams the students communicated their thought processes verbally and through nonverbal interactions. To augment the collection of students' cognition, audio was supplemented with video (Derry, 2007; Gero & Kan, 2009). While the participants were either analyzing or gathering information independently, or even gesturing, the video helped fill potential data gaps in the audio. Video and audio together are a rich information source from which multiple data were extracted. Verbal protocols attempt to minimize leading questions and influences from the administrator to collect authentic cognition from the research participant(s) (Ericsson & Simon, 1980). Additionally, there was tracking software, SpectorPro®, on the desktop computer to capture the students' activities during the design challenge. This study collected verbal, video, computer data, and design sketches during the design challenge as a means to analyze and further understand student systems cognitive processes and strategies.

### **Post-hoc Focus Group**

Immediately following the design challenge, team members participated in a focus group interview (Atman, et al., 2008; Charles & d'Apollonia, 2003). The students were asked to reflect on their design challenge (Cross, 2002; Zachary, et al., 2000). This focus group interview gave the researcher the opportunity to ask probing questions regarding the systems cognitive processes and strategies employed in the challenge that

might have been asked during the protocol, but would possibly change the students thinking with leading questions. The questions queried the students on how they framed the problem, came to a solution, and what strategies they used, if any (Appendix F). The focus group data were triangulated with the audio, video, and tracking data from the design challenge along with the design sketches.

### **Data Analysis**

Analysis of the quantitative and qualitative data for this mixed method triangulation research study was performed concurrently. After the audio and video from the design challenge and the interview were transcribed, the data were segmented and coded (Chi, 1997). The computer movements were also included in the coding where appropriate. To ensure inter-rater reliability, the data were be coded by more than one researcher (solicited graduate students). The coding analysts were trained on proper coding. Cohen's Kappa was calculated between the coders. The frequency counts and time on task between each code were analyzed using non-parametric data analysis techniques. The audio and video data from the design challenge, audio and video data from the post-hoc interview, the tracking data, and the design artifact were triangulated for evidence of systems thinking and emerging themes or phenomena as well. The coded data were also analyzed using measures of centrality. Betweenness, closeness, and degree were calculated to give the relative significance of the codes.

## **Pilot Study**

A pilot study was performed to gauge feasibility, to optimize methodology, and to collect preliminary data. The pilot consisted of one dyad of students. The analysis of the pilot included: assessment of the team size, the duration and scope of the design challenge, technical feasibility and optimization, and administration of the design challenge, interview, and the demographic questionnaire. The lessons learned from the pilot study were implemented into the full study. The pilot study helped ascertain if enough data were generated from the two students. Additionally, the pilot helped answer the following questions: Will the current design challenge shed light on systems thinking? Is an hour enough time for the students to feel comfortable about their design and does it generate sufficient verbalization? What questions are helpful, what are not, and what new questions should be added to the post hoc focus group and demographic questionnaire? Will students need more scaffolding through materials and clarification? However, too many specific materials may also lead the students to a canned solution. Giving students a contrived “box of tools” may artificially set constraints on the students. Furthermore, the pilot study helped to understand and analyze student’s systems thinking through the FBS framework. The data from the pilot study was also used for training the coding analysts. After the pilot study was analyzed, decisions to alter and improve the complete study were implemented.

## Data Segmenting and Coding

After the audio was transcribed, the data were segmented and coded while simultaneously viewing the video source. The computer movements were also included in the coding and analysis. The process of segmenting and coding has been used in many verbal protocols (Adams, et al., 2003; Atman, et al., 2008; Chi, 1997; Cross, et al., 1994; Gero & Lindemann, 2005; Robertson, 1990). The audio source was segmented into utterances. The segmenting and coding was performed simultaneously. Each segment contained only one code assignment. If the utterance contained more than one code, it was further segmented.

The definitions for coding the FBS framework are listed in Table 2.

Table 2

### *Working Definitions for the Function-Behavior-Structure Framework*

Code	Description
Function (F)	The purpose of what it is for or why
Requirements (R)	The requirements set forth by the customer
Expected Behavior(Be)	Expected for the structure, what it does, or could do
Derived Behavior(Bs)	Derived or taken from the structure, analysis
Structure (S)	Components of an object and their relationship, what it is
Documentation (D)	Annotations used during the design process
Other (O)	Utterances that are not related to design

The FBS training document is found in Appendix G. These definitions were compiled from design, science education, and engineering education (Gero & Kannengiesser, 2004; Hmelo-Silver, et al., 2000; Katehi, et al., 2009). “The SBF

framework allows effective reasoning about the functional and causal roles played by structural elements in a system by describing a system's subcomponents, their purpose in the system, and the mechanisms that enable their functions" (Hmelo-Silver & Pfeffer, 2004, p. 130). From their results, Hmelo-Silver and Pfeffer (2004) found that novices were more likely to spend more time on structure than on behaviors and function. The FBS framework can provide not only a description of systems cognitive processes and strategies, but it may also provide educational implications for engineering design.

The data for this study were segmented and coded by two coding analysts. The materials for training the analysts were taken from a previous research study, the pilot study, literature, and notes from John Gero's training session. They read the articles searching for the definitions proffered by Gero (1990) and Hmelo-Silver (2000) in their studies. The coding analysts were two graduate students in the Engineering and Technology Education doctoral Program at Utah State University. The training began before the pilot study was performed.

The coding analysts were given an orientation of the research and the FBS framework. The analysts were provided with the FBS Training Document (Appendix G) and journal articles relating to FBS and systems thinking. The orientation included actual coding of a previous engineering design challenge. The researcher and analysts worked together using working definitions of FBS to segment utterances and assign them codes. At first there was more disagreement and a lack of understanding of the research methodology. The researcher made many attempts to draw analogies and dispel misconceptions. The orientation was more than the training of how to use the FBS

framework for coding. It also included research methodology with verbal protocols and how systems thinking fit within the complexity science epistemology. Furthermore, the FBS framework employs terms that are used quite differently in other domains. For example, computer programming (the background of one of the analysts) uses the terms function and structure to describe an object or subroutine; which is a description quite distinct from the FBS framework definitions.

The analysts were then tasked with coding a small sample of data separately. The analysts were brought back together multiple times to reconcile their coding with the researcher arbitrating. Each analysts coded 65% of the transcripts with a 30% overlap of each others' coding (Gero & Kan, 2009; Kan & Gero, 2010). The overlap occurred at the beginning, middle, and end of every recorded session. The segmenting, coding, and overlap were performed in Microsoft® Office Excel 2007®. The transitions from one code to the next were also summarized and analyzed. Each coded segment received only one FBS codes. These codes and their transitions were used for further quantitative analysis and can be correlated with the definitions given in Table 2. Table 3 is a sample of coded data from a design challenge using the FBS framework.

Table 3

*Coding in the Function-Behavior-Structure framework (Gero & Kan, 2009)*

Coding	Segment
Function (F)	“that’s the standard plain thermal paper”
Expected Behavior (Be)	“either patterns or line types”
Derived Behavior (Bs)	“if you lift an optical mouse slightly off the page you’ll see the pattern it creates”
Structure (S)	“a sledge or a snowboard”

### **Quantitative Data – Research Questions #1 and #2**

After the coding was completed, descriptive statistics were determined for each code and their transitions; such as the means, standard error of the mean, and plots. Although the number of participants was low, the number of utterance data points was high. Therefore, measures of centrality were performed (Lee, et al., 2003; Sosa, et al., 2007). The three measures used were degree, betweenness, and closeness. Degree is the measure of the number of connections to a node or code. Betweenness is the measure of the path distance between codes. Closeness is the distance of the nodes to each other topographically. These measures yielded a relative importance and usage of each code and transition. The software used in the analysis was Microsoft® Office Excel® 2007 (Version 12.0.6535.5002, Microsoft, Redmond, WA) and UCINET (version 6.289, Analytic Technologies, Lexington, KY).

### **Qualitative Data – Research Question #3**

“Qualitative research is characterized by the collection and analysis of textual data (surveys, interview, focus groups, conversational analysis, observation, ethnographies), and by its emphasis on the context within which the study occurs” (Borrego, et al., 2009, p. 55). There was a qualitative analysis of the collected responses in this mixed method triangulation study. The data sources were: audio and video responses from the design challenge, audio and video responses from the post-hoc focus group interview, the software tracking responses from the computer, and the design artifact. These data were triangulated against each other for systems thinking through the

FBS framework. Additional unanticipated themes or phenomena also surfaced during this process. Hmelo-Silver et al. (2000) used a similar methodology in their study. A quantitative measure was collected and analyzed in addition to the student interviews, observations, and the design artifact. Even though the FBS framework was successfully used to study the students' complexity thinking quantitatively, the qualitative nature of the study allowed new phenomena to surface through further analysis, such as the inter-collaborative interactions coined by Hmelo-Silver et al. as "gallery walks." This research was also open to and sought for new themes by poring over the data outside of the FBS framework and the resulting segmenting and coding.

### **Summary**

This exploratory research study followed the triangulation mixed methodology to answer the research questions. There were 12 students, or six dyads from an exemplary regional high school engineering program. Verbal and video report data were collected to capture the students' cognition. There was also a post-hoc focus group interview allowing the researcher to query the students as to their decision making processes and strategies. The students were asked to design a window mechanism considering engineering, ergonomic, and social variables and constraints. The audio and video data from the design challenge and the interview were transcribed, segmented, and coded. Emergent themes were analyzed qualitatively as they developed and the data were also coded using the FBS framework. These coded data were analyzed using descriptive statistics. The transitions or processes were analyzed by measures of centrality. The implications and



pedagogical insights from this study were shared with the participating teacher. The results of this research provide a basis of how high school students think with open ended engineering design problems. The results also aid in the development of curriculum, instructions, and interventions in systems thinking.

## CHAPTER IV

### RESULTS

The purpose of this research was to understand the systems cognitive processes and strategies used by high school students within the Function-Behavior-Structure (FBS) cognitive analysis framework while engaged in collaborative engineering design challenges. Cognitive issues are mental activities used during a design challenge while the processes are the way in which the issues are approached. This section will discuss the results and analysis of the collected data.

The FBS framework was applied to the coding of the audio, video, and computer movements. The codes generated from these data were analyzed using descriptive statistics and measures of centrality. Additionally, the data were analyzed for emergent themes and patterns outside of the FBS framework.

#### **Sample Description**

##### **Pre-engineering Program**

Engineering and Technology programs may widely differ from school to school (Starkweather, 2008). This difference may be influenced by the curriculum, administrative support, or by the individual teachers. This research was performed at Northridge High School (NHS). NHS is located in Layton, UT and is part of the Davis County School District. NHS claims to have a pre-engineering program. Although there is no set definition or criteria for “pre-engineering”, the name reflects the attitude and

aspirations of the program. The pre-engineering program at NHS is lead by a retired engineer turned educator. Prior to joining NHS's pre-engineering program, the teacher in this study was a mechanical engineer for over 20 years. In addition to teaching engineering, he is a dedicated astronomer and detail-oriented tinkerer. Although the teacher knew that not all students would become engineers, he would often remark how a certain part of the curriculum or pedagogy would, "help train our future engineers." The teacher expected the students to model engineering ways of thinking and made frequent references to his previous experience. The teacher walked, talked, and acted like an engineer hoping the students would gain an authentic engineering education experience.

The curriculum used by this program was Project Lead the Way's (PLTW) Pathway to Engineering. PLTW is non-profit organization that offers STEM curriculum to middle and high schools. There are many STEM curricula available, yet PLTW is the most ubiquitous pre-engineering curriculum across the US. NHS was able to offer six courses from PLTW with specializations in civil and manufacturing engineering. PLTW has a standard curriculum and requires that instructors take PLTW professional development prior to teaching each course. The PLTW curriculum is quite scripted, yet teachers are able to expand on and alter their pedagogy as they see fit. The teacher in this study appreciated the PLTW curriculum and stayed close to the suggested lesson plans, but felt that "It did not offer the rigor found in college engineering courses." Overall, the teachers and administrators at NHS were content with what PLTW afforded the students.

## **Student Participants**

This study included 12 student participants from NHS. All of the participants were males. Eleven students were from European descent and there was one Latino student. Their mean ( $M$ ) age was 17.3 years with a standard error of the mean ( $SEM$ ) = .22. The composition of the participants was eight seniors, three juniors, and one sophomore. Their overall high school grade point average, based on a 4.0 scale, was ( $M = 3.61$ ,  $SEM = .12$ ). The students had taken ( $M = 3.6$ ,  $SEM = 1.24$ ) engineering courses. Eleven students claimed their neighborhood was suburban and one student claimed an urban neighborhood. All 12 students' parents had obtained at least an associate's degree. As a note, all names used in this study are pseudonyms.

## **Pilot Study**

A pilot study was completed to assess study feasibility, to optimize the data collection technique, and to provide preliminary data for coding analyst training. The pilot consisted of one dyad of students. The pilot study also took place at NHS. This was the same population and classroom as the full study data collection. Analysis of the pilot included assessment of the team size, duration and scope of the design challenge, technical feasibility and optimization of the data collection equipment, and administration of the design challenge, interview, and demographic questionnaire. The data from the pilot study were not included in the full study as there were differences in how the pilot and full study were administered.

## **Study Feasibility**

One of the primary questions to be addressed by the pilot study was the feasibility of the scope, duration, team size, and data collection of the design challenge with a dyad of high school pre-engineering students. This was a concern because there were not solid criteria from past research. The scope of the design challenge was within the student's capabilities. Although the students were not personally familiar with double hung sash windows, they were able to come to a detailed understanding of the function and workings through websites, videos, and drawings on the Internet. Evidence of their understanding included the audio and video of their design challenge, the audio of the post-hoc focus group interview, and their sketches. The one hour duration of the design challenge allotted was sufficient for the students to generate a design solution. In addition, the students in the pilot study only needed 49 minutes to complete their design. Therefore, the scope and duration of the design challenge were deemed feasible. Only one dyad in the full study used the complete hour for their design.

The feasibility of the data collected was also under investigation during the pilot study. Previous studies (Gero & Kan, 2009; Kan & Gero, 2010) were able to obtain at least a couple hundred coded segments for each participant unit. The percentages of codes found in the pilot study were consistent with Gero's research. Additionally, the resulting percentages of FBS codes from the pilot were consistent with Hmelo-Silver and Pfeffer's (2004) findings for novices. The results from this study are further explained in the full study section. Furthermore, the work performed by Denson et al. (2010) suggests that teams of high school students generated ample data in a similar design challenge if

the audio data were supplemented and triangulated with video and design artifacts.

Working in teams of two, the students verbalized and communicated frequently yielding useable research data. Therefore, the data collection supports the feasibility in answering the study research questions.

Another question was if the current design challenge shed light on systems thinking. Although the pilot study could not fully answer this question, it appeared that the students were in line with previous studies (Hmelo-Silver & Azavedo, 2006; Hmelo-Silver & Pfeffer, 2004; Jacobson & Wilensky, 2006) that non-experts reference structures more than functions or behaviors (Lehrer & Schauble, 1998; Lehrer, Schauble, Strom, & Pligge, 2001). In the pilot study, the students referenced structures in 51% of the coded segments. Furthermore, the number of transitions in each category was summed and the number of transitions was also consistent with findings in Kan and Gero's recent study (Kan & Gero, 2010).

Another aim of the pilot was to ascertain whether students had enough material, administrative, and/or computer support to complete the design challenge. The students did not ask for additional material resources to aid in their design. Additionally, the duration of the task was extended by 15 minutes in order to collect sufficient data when compared to Gero's study with college engineering students. The students were able to generate a satisfactory final design proposal in as much as they were able to produce a sketch of their design accompanied with a verbal explanation. Therefore, the duration and scope of the design challenge appeared to generate sufficient data to help answer the research questions.

### **Optimize Data Collection Techniques**

The pilot study was also performed to optimize and refine the data collection technique. The first task was to create an in vitro environment that was as similar as possible to the students' classroom experience. Therefore, the pilot study took place at the same classroom as is offered for the upper level engineering courses. With the help of the instructor, a classroom computer station was also employed during the pilot study. From the Denson et al. (2010) study, the students felt slightly uncomfortable with the perceived "intimidating" video and audio equipment. Originally, a full size camcorder on a professional tripod was going to be used to record the video. The camcorder was positioned to capture the sketches and gestures from the students. However, when setting up the pilot study, through their body language and frequent attention given to the video recorder it was decided to try an additional approach. A small digital video recorder was placed in front of the students on an adjacent table. The widescreen format of the video recorder satisfactorily captured the relevant video. A small digital audio recorder was also placed in front of the students to record verbalizations and other pertinent audio. The students later responded in the interview that the recording equipment used in this study was not imposing. The video, augmented with other collected data, provided sufficient data and insight to recreate the design process without the camcorder.

The pilot study was also used to optimize the demographic questionnaire and post hoc focus group interview. The question asking the student's number of engineering classes they have taken was deleted as that number was deduced from the list of engineering courses taken. During the post hoc focus group interview, questions were

sometimes answered by the students as they elaborated on a previous question. Therefore, the administrator had to be cognizant of the upcoming questions. For example, the students were asked which ideas worked and which did not work. In answering that question, the students answered the following question of how they compared their ideas. Therefore, in the full study the administrator had to be familiar with the questions as to not repeat themselves.

### **Coding Analyst Training**

The segmenting and coding was completed by two separate analysts who received training from the researcher. The training commenced with the analysts becoming familiar with the definitions of the FBS framework from the literature. The researcher and the coders worked together to code a sample of audio and video from the preliminary study. This activity brought the coding team to a closer agreement on how to code for FBS. The coders then segmented and coded sample data on their own. Their results were compared and arbitrated with the researcher until there was an acceptable agreement. The comparisons, or agreement between analysts' results, were analyzed using Cohen's kappa with a threshold of .70.

The overlap was done at different intervals (sampling) throughout various data points at the beginning, middle, and end of each session. After completing the sample data coding, the analysts segmented and coded the design challenge. The analysts made progress, but were merely at 50% agreement. With the pilot data collected, the analysts and researcher convened again to practice coding. Once again, the training involved not



only FBS coding, but methodology alike. The analysts returned to segmenting and coding a small portion of the pilot data, 50 lines. Upon review of a small portion of the pilot data that had been segmented and coded, it was found that the analysts' coding results were not in accord with the working definitions, nor with each other. Although the coding analysts felt comfortable and confident with the working definitions, they had not yet sufficiently been trained. With arbitration, the percent agreement was above 80%, but individually, it was in the 60% range. Therefore, the training had to be extended over six training sessions, yielding a significant portion of the coding time to training.

The analysts were tasked again with individually segmenting and coding a new portion of the design challenge. The training involved reviewing why and how each analyst segmented and coded their portion. The training also involved coming together to resolve any concerns. The concerns of the analysts and researcher included coding definitions and procedures. After the final training, the analysts were able to individually code 1917 segments codes yielding a satisfactory percent agreement of 93.2%. Cohen's kappa was also calculated at 0.89, exceeding an accepted reliability coefficient of 0.7 in the social sciences (Schloss & Smith, 1999).

The analysts stated that the segmenting and coding was a tedious task. Additionally, the researcher found that training was more intensive and time consuming than originally planned. Nevertheless, the intense training paid off with satisfactory segmenting and coding results.

## Gero's FBS Framework

This research aimed to follow Gero's FBS codes and definitions for research questions one and two. Gero's framework and the relating nuances were used to train the coding analysts. However, the literature relating to Gero's definitions were not exhaustive. Therefore, working definitions were set according to personal communication with Gero and colleagues. The idea of "information gathering" is present in various engineering design models (Atman, et al., 1999; Dym, et al., 2005; Eide, et al., 2002; Hailey, et al., 2005). Gero's model does not include "educating oneself." Therefore, whenever the student participants educated themselves by searching the internet or some other means, it was coded as "Other (O)." The following is segment coded as "O": "So, do you want to check out some other websites?" However, if the student participant drew upon memory in analogical reasoning as it pertained to the design, it was coded expected behavior (Be), e.g., "I have a tire pump for a bike, a foot pump. But [you] could just push it down and force air through it. We could use the same principle."

An additional coding protocol was to treat the student participants as a unit of one. If one student participant made an utterance that was coded and the second student only repeated the same idea or merely reiterated what the previous student participant stated, the segment was not given a separate code, e.g.,

Caleb: "Like the foot pedal for the drum."

Taylor: "Okay, I know what that is."

However, if the second student participant expanded upon the idea or made an utterance with a different coding, the two segments were coded separately, e.g.,

Taylor: “Like with the cranes. You know how cranes have the – I don’t know what it’s called – but...”

Caleb: “They have kind of like a car jack.”

The complete working definitions and unique nuances of FBS used for this study can be found Appendix G.

## **Quantitative Analysis**

### **Research Question #1**

The first research question of this study was, what are the mental issues, activities, and operations used by high school students when attempting an engineering design challenge analyzed through the FBS framework? To address this question high school students’ audio, video, and computer movements were recorded, transcribed, segmented, and coded.

**Descriptive statistics.** The student participants generated sufficient segments for coding through verbalizations augmented by the video and computer movements (Gero & Kan, 2009; Atman, et al., 2007; 2009; Hmelo-Silver, et al., 2000; Mosborg, et al., 2006). The video and computer movements did not receive separate coding, although they were segmented as needed to clarify the verbalizations. The following segmentation is an example of where the video and computer aided in understanding the students’ cognition.

Eugene    Put a pulley here [sketches a pulley on top left of window] so it will go down through there [sketches a pulley on bottom left of window] and another over to the wall [sketches pulley below window] so there’s

- two of them there. So [the cord] runs underneath both of them [glances over to Skylar for affirmation].
- Skylar Yeah.
- Eugene And it goes up to one on the ceiling and over to another one so when they pull it down [motions pulling down a cord], they pull it [the window] down.
- Skylar Yeah and looks like that's a lot of... [turns from sketch to look over at the window diagram displayed on the computer monitor].
- Eugene 'Cause if you were to just put one on the floor like this [sketches another pulley], then you have to [gestures two hands lifting together].
- Skylar So, I don't think a pulley system would work.
- Eugene It would for the top one.
- Skylar Eventually, yeah, but it is a lot of work to get it down to the bottom.
- Eugene [We'll] figure something else for the bottom.  
[Both students turn to the computer and look up Americans with Disabilities act on wikipedia.com].

Without the video, the sketching and the gestures would have been difficult, if not impossible, to capture. The computer movements elucidated what the students were doing on the computer.

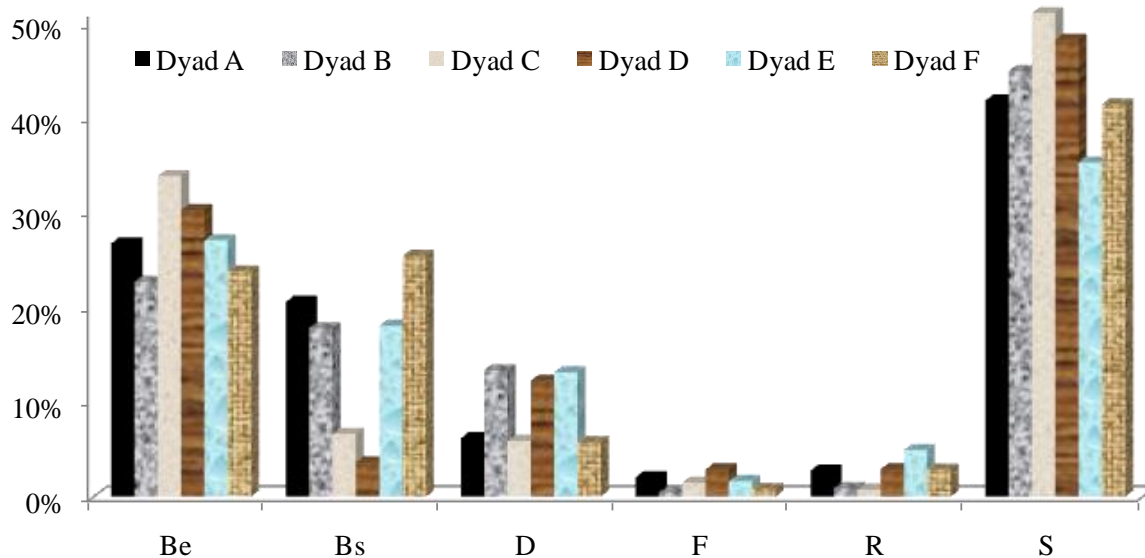
There were 1,917 segments coded. Of these coded segments, 1,012 (52.8%) were coded within the FBS framework. The total FBS codes are found in Table 4 with their descriptive statistics of mean, standard error of the mean, and percentage.

Table 4

*Descriptive Statistics for Function-Behavior-Structure Coding*

Code	<i>M</i>	<i>SEM</i>	%
Expected Behavior (Be)	44.83	3.63	26.6%
Derived Behavior (Bs)	28.00	8.62	16.6%
Documentation (D)	15.67	3.23	9.3%
Function (F)	2.33	0.42	1.4%
Requirements (R)	4.00	0.93	2.4%
Structure (S)	73.83	9.40	43.8%

The percentages were calculated from the total number of FBS coded segments. Structure (S) was the most prevalent code at 43.8% with the lowest being Function (F) at 1.4%. Nearly one-tenth of the coding was given to the teams documenting (D) their design. This was done through sketching and list making. Note that only utterances that pertained to documentation were coded with (D). There were many instances when the students were “documenting.” Yet, without an utterance there was no coding attached. Figure 3 is a graph of the percentage of FBS codes by team. The graph shows that the most common



*Figure 3.* Function-Behavior-Structure code distribution for all dyads. Be = Expected behavior, Bs = Derived behavior, D = Documentation, F = Function, R = Requirements, S = Structure.

code for all dyads was structure and the least common were both function and requirements.

## **Research Question #2**

The second research question of this study was, what mental processes, approaches, and transitions are present when high school students attempt an engineering design challenge analyzed through the FBS framework? The processes are operationally defined as transitions from one FBS code to another. A code may transition into itself. Similar to the previous research question, the high school students' audio, video, and computer movements were recorded, transcribed, segmented, and coded. Furthermore, the code transitions were analyzed using measures of centrality: degree, betweenness, and closeness using UCINet.

**Data analysis in UCINet.** Before the data were analyzed in UCINet, the data were verified against the actual counts of the coded data. These data were input into a text file for uploading into UCINet. UCINet prepared a file containing a 6 x 6 matrix of valued data for each dyad. A matrix consisted of six rows and six columns containing each FBS code. The diagonal of the matrix constituted the codes transitioning to themselves, as the coding of this dataset allowed codes to transition as such. A node coded "structure" could transition back to a "structure" node. This resulted in non-zero values for the matrix diagonal. The matrices were then verified against the imported text files for accuracy. Due to the non-zero values of the matrix diagonals, the matrices were analyzed as asymmetrical directed value data. The equations for the measures of centrality may be found in Appendix H.

**Degree.** Degree is the measure of the number of transitions to a node. In this research study, it is the number of transitions coming into (InDegree) or going out of (OutDegree) a specific FBS code. In others words, the transition from one FBS code to another. The raw count of Freeman’s OutDegree of Centrality was calculated for each dyad as summarized in Table 5. As this research study is represented by a network of sequential events, the InDegree is the same as the OutDegree with two exceptions; the first and the last FBS codes. It was decided to present the OutDegree, but the InDegree results are similar. The raw number count for OutDegree is similar to the distribution of counts for the FBS code, see Table 4. Structure had the greatest number of transitions, 42.7%, and function had the fewest, 1.3%.

Table 5

*Freeman’s OutDegree for FBS Codes by Dyad – Raw Number Counts*

FBS Code	Dyad A	Dyad B	Dyad C	Dyad D	Dyad E	Dyad F	Total	<i>M</i>	<i>SEM</i>	%
Be	38	51	46	42	32	57	266	44.33	3.68	27.1%
Bs	30	40	9	5	20	62	166	27.67	8.67	16.9%
D	9	30	8	17	16	14	94	15.67	3.23	9.6%
F	3	1	2	4	1	2	13	2.17	0.48	1.3%
R	4	2	1	4	4	8	23	3.83	0.98	2.3%
S	61	100	68	56	32	101	418	69.67	10.93	42.7%
Subtotal	145	224	134	128	105	244	980	163.33	23.12	

*Note.* Be = Expected behavior, Bs = Derived behavior, D = Documentation, F = Function, R = Requirements, S = Structure.

Although Structures had the highest number of outgoing transitions, it did not always have the highest calculated degree value. Table 6 shows the value of Freeman’s OutDegree for all dyads.

Table 6

*Freeman's OutDegree for FBS Codes by Dyad*

FBS Code	Dyad A	Dyad B	Dyad C	Dyad D	Dyad E	Dyad F	Total	<i>M</i>	<i>SEM</i>
Be	5	4	6	6	6	5	32	5.33	0.33
Bs	5	4	4	3	4	5	25	4.17	0.31
D	4	4	3	5	5	3	24	4.00	0.37
F	2	1	1	2	1	2	9	1.50	0.22
R	3	2	1	3	3	4	16	2.67	0.42
S	5	5	4	5	3	5	27	4.50	0.34
Subtotal	24	20	19	24	22	24	133	22.17	0.91

*Note.* Be = Expected behavior, Bs = Derived behavior, D = Documentation, F = Function, R = Requirements, S = Structure.

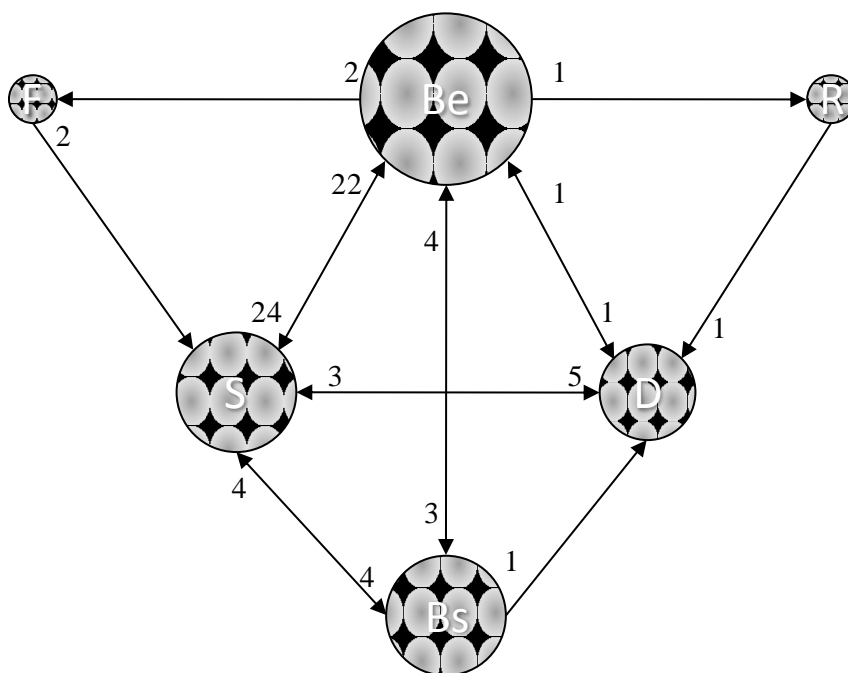
Expected behavior had the greatest mean degree value of ( $M = 5.33$ ,  $SEM = .33$ ).

Expected behavior also had the highest degree value for five out of six dyads. The results suggest expected behavior had the highest OutDegree value as it had the most transitions to other codes. Structures, derived behavior, and documentation could be grouped with similar means, ( $M = 4.50$ ,  $SEM = .34$ ), ( $M = 4.17$ ,  $SEM = .31$ ), ( $M = 4.00$ ,  $SEM = .37$ ), respectively. Requirements and function would form a third grouping with ( $M = 2.67$ ,  $SEM = .2$ ), ( $M = 1.50$ ,  $SEM = .22$ ), respectively. Function had the lowest degree value for all dyads.

Figure 4 is an illustration of the FBS degree network for Dyad C. The figure displays the FBS codes and the transitions to each other code (if any). The number closest to the code represents the number of out transitions to the corresponding code. The arrow heads represent directionality of the transition. The size of the code circle is the respective degree value. For example, structure (S) only transitioned to documentation (D) three times, while documentation (D) transitioned to structure (S) five times.



Documentation (D) had a degree value of two and requirements (R) had a degree value of one. Although structures (S) had the highest number of degree raw counts, expected behavior (Be) played a more central role in transitions for Dyad C.



*Figure 4.* Freeman's OutDegree network for Dyad C.

*Note.* The size of the circle is proportional to the calculated Freeman's Out Degree value for the FBS code. Each line represents a link, with the arrowhead representing the direction of the link. The number represents the raw number of out transitions from the code to which it is most closely placed. Be = Expected behavior, Bs = Derived behavior, D = Documentation, F = Function, R = Requirements, S = Structure.

## Betweenness

Betweenness is the measure of the how integral a code is to all paths from any code to any other. Freeman's Betweenness values were calculated for each dyad and are summarized in Table 7.

Table 7

*Freeman's Betweenness for FBS Codes by Dyad*

FBS Code	Dyad A	Dyad B	Dyad C	Dyad D	Dyad E	Dyad F	Total	<i>M</i>	<i>SEM</i>
Be	1.0	0.0	5.0	5.0	5.3	4.8	21.2	3.53	0.97
Bs	3.3	3.0	0.0	0.0	0.0	1.3	7.7	1.28	0.63
D	1.3	0.0	4.0	1.5	3.0	0.0	9.8	1.64	0.66
F	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.17	0.17
R	0.0	0.0	0.0	0.5	5.3	1.0	6.8	1.14	0.85
S	3.3	7.0	4.0	4.0	0.3	2.8	21.5	3.58	0.88
Subtotal	8.99	10	13	11	13.99	10.99	67.97	11.33	0.76

*Note.* Be = Expected behavior, Bs = Derived behavior, D = Documentation, F = Function, R = Requirements, S = Structure.

Betweenness in this study would suggest that a cognitive activity is a stepping stone or gateway to another activity. It is possible for a code to have a value of “0” if it did not have an integral transition path. Each dyad had at least one code that had a betweenness value of “0.” The results from betweenness calculations suggest that when the students moved from one code to another, the code that would act as a critical intermediary would be structures ( $M = 3.58$ ,  $SEM = .88$ ), and only slightly behind would be expected behavior ( $M = 3.53$ ,  $SEM = .97$ ). Expected behavior had the highest betweenness for four dyads with Structures having the highest betweenness for two dyads. Function had the lowest mean betweenness value ( $M = 0.17$ ,  $SEM = .17$ ). With the exception of one dyad, function had a betweenness value of 0. Figure 5 is an illustration of the FBS betweenness network for Dyad C. Like Figure 4, this figure displays the FBS codes and the links, or transitions, to each other code. The arrow heads represent directionality of the links. Directionality is the sequential order from one code to another.

The size of the code circle is proportional to the betweenness value. For example, for function (F) to go to requirements (R) it would first have to go through structure (S) then through expected behavior (Be). Note that one cannot transition from function (F) to expected behavior (Be) due to directionality being only one way. With further observation, structure (S), expected behavior (Be), and documentation (D) all have bidirectional links to each other negating the need to transition between other codes. Expected behavior has the greatest number of links and strategic paths, thus it has the greatest betweenness value of five for Dyad C.

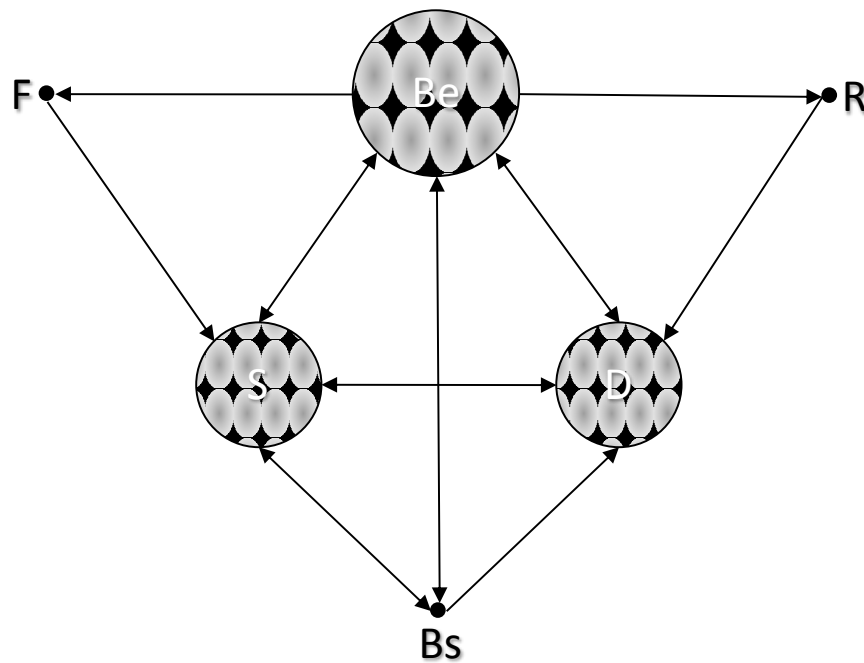


Figure 5. Freeman's Betweenness network for Dyad C.

*Note.* The size of the circle is proportional to the calculated Freeman's Betweenness value for the FBS code. Each line represents a link, with the arrowhead representing the direction of the link. Be = Expected behavior, Bs = Derived behavior, D = Documentation, F = Function, R = Requirements, S = Structure.

## Closeness

Closeness is the proximity of one code to all of the other codes following the path of directional links. Closeness is calculated by taking the reciprocal of the sum of all the distances of one code to all others following the directional links. Freeman's Closeness for each dyad is summarized in Table 8.

Table 8

### *Freeman's Closeness for FBS codes by Dyad*

FBS Code	Dyad A	Dyad B	Dyad C	Dyad D	Dyad E	Dyad F	Total	<i>M</i>	<i>SEM</i>
Be	0.14	0.14	0.14	0.17	0.17	0.20	0.96	0.16	0.01
Bs	0.20	0.17	0.11	0.14	0.11	0.14	0.87	0.15	0.01
D	0.17	0.14	0.17	0.13	0.14	0.14	0.89	0.15	0.01
F	0.13	0.11	0.10	0.14	0.13	0.13	0.73	0.12	0.01
R	0.13	0.09	0.10	0.13	0.17	0.13	0.73	0.12	0.01
S	0.20	0.17	0.17	0.20	0.13	0.17	1.03	0.17	0.01
Subtotal	0.96	0.82	0.79	0.90	0.84	0.90	5.21	0.87	0.03

*Note.* Be = Expected behavior, Bs = Derived behavior, D = Documentation, F = Function, R = Requirements, S = Structure.

Structures had the highest closeness mean value ( $M = 0.17$ ,  $SEM = 0.01$ ).

Structures had the highest closeness value for four dyads, with expected behavior the highest for two dyads. The lowest closeness values were function and requirements, ( $M = 0.12$ ,  $SEM = 0.01$ ).

Figure 6 is an illustration of the FBS closeness network for Dyad C. As in Figure 4, this figure displays the FBS codes and the links, or transitions, to each other code. The arrow heads represent directionality of the links. The size of the code circle is proportional to closeness value.

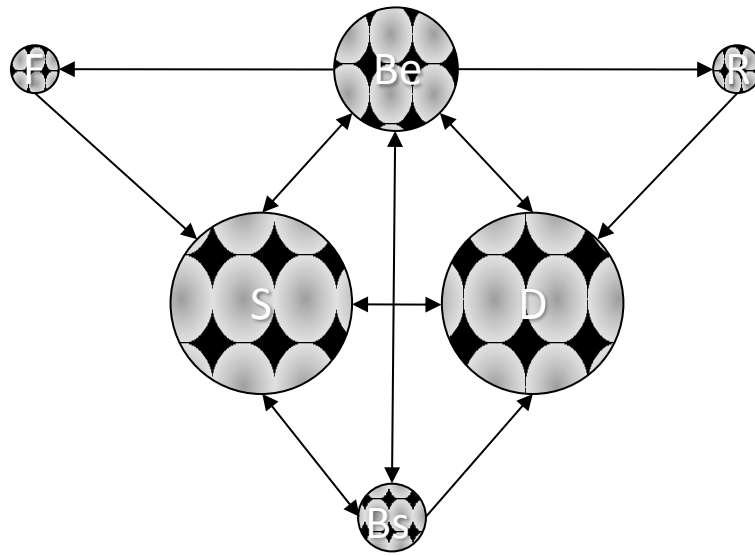


Figure 6. Freeman's Closeness network for Dyad C.

*Note.* The size of the circle is proportional to the calculated Freeman's Closeness value for the FBS code. Each line represents a link, with the arrowhead representing the direction of the link. Be = Expected behavior, Bs = Derived behavior, D = Documentation, F = Function, R = Requirements, S = Structure.

For example, in order for function (F) to go to requirements (R) it would take three steps: one to structures (S), another to expected behavior (Be), and finally to the destination requirements (R). Another example, for function (F) to go to derived behavior (Bs) it would take two steps going through structures (S). The closeness value is calculated by performing this analysis to all other codes. These numbers are summed to obtain farness; the reciprocal of farness yields closeness.

The measures of centrality were calculated for all of the dyads as a whole. However, the combined results yielded meaningless figures. The figures contained links in all directions to all nodes.

## **Quantitative Summary**

The first two research questions of this study sought to understand what mental activities, issues, or components were used by high school students and how they transitioned in an engineering design problem using the FBS framework. The coded data were tabulated and descriptive statistics were generated. The students predominantly demonstrated the use of structures in their design. However, when transitioning from one code to the next, expected behavior had the highest degree value. Along with structures, expected behavior was pivotal in betweenness and closeness.

## **Qualitative Analysis – Research Question #3**

Research question #3 asked, are there emerging qualitative themes and phenomena as they relate to systems thinking in engineering design? If there are themes or phenomena, how can these themes and phenomena be analyzed and interpreted? The data sources included audio and video responses from the design challenge, audio and video responses from the post-hoc focus group interview, software tracking movements on the computer, and the design artifact. The data were triangulated with each other to better understand systems thinking.

Qualitative analysis was performed by repeatedly poring over the data outside of the FBS framework and the resulting segmenting and coding. In other words, FBS was not used as a frame of reference for this analysis. Undoubtedly, the FBS framework had influenced the researcher's thinking. However, the FBS framework was not intentionally used or referenced in the qualitative analysis. The analysis was informed by literature in

complexity as well as literature in engineering design. The following themes were identified and explored: multiple interconnected variables, optimization, and unboundedness. The qualitative analysis involved looking at all data sources in tandem. All of the videos were viewed to get a feel for the study. Following the viewing, the videos were analyzed along with the transcripts, the computer movements, and the corresponding sketches by dyad. The results of this study yielded three new additional themes: sketching, analogical reasoning, and design challenge relevance. With this step completed, all dyads were analyzed looking for the common themes listed above. As an idea or pattern evolved, all the data sources were analyzed to further understand the phenomenon. The phenomena found in this study will be described below.

## **Systems**

### **Interconnected Variables**

Engineering design is a complex process with multiple interconnected variables that are technical and nontechnical alike. Technical variables may include mechanical advantage, friction, and tensile strength. Nontechnical variables may include ergonomics, maintenance, and the social environment. The human component as designer and client are critical (Brophy, et al., 2008; National Academy of Engineering, 2004, 2005). The complexity described here should not be confused with the term complicated. Although complicated problems are present in engineering design, complexity is organic with dynamic variables, resulting in interactions. Towards the beginning of one design session, a dyad commented about the complexity of the challenge.

Ryan I thought we were only trying to overcome gravity here.  
 Robert We are trying to do lots of stuff.

Perhaps one of the most complex variables in engineering design is the human interface. To understand design, one should not merely focus on the finished product, but should also include the coming together of designers and other key players, the constraints of manufacturing, maintenance of the designed object, and role of the end user (Bucciarelli, 1994).

The students in this design challenge considered interconnected variables with a primary focus on the unique end users; tenants of a nursing home with various limited physical abilities. Every dyad was cognizant of the nursing home tenants and made multiple references to their limited abilities during their design. One dyad focused on possible tenants with arthritis.

Bart Then we'll have a safe, arthritis-friendly lever.  
 Ricky Or if they are too old to even like push down on it, they can just lean on it.

Subsequently, this dyad generated a solution allowing the tenants to lean against a large button on the wall to activate their system. Another dyad took the idea of ergonomics further by considering access by those in a wheelchair. The students were discussing a hand crank as part of their design:

Sean Freaky, I think that [a crank] would be too little. I mean, we have like a huge one for the grandmas. A steering wheel even.  
 Angel Yeah, we could even put it at the bottom, so like if they're in a wheelchair too.

When the students made references to the tenants, they most often mentioned terms such as “wheelchair” and “arthritis.” All dyads made considerations for the disabled while four dyads actually performed online searches of the Americans with Disabilities Act (ADA).



This may have been influenced by a link given on the design brief regarding the ADA. Yet, it was up to the students if they wanted to type in the address and visit the website. The students sought to implement ADA guidelines in their design. The students wanted hard numbers that could be used in calculations, such as “five pounds of force to open and close.” Yet, most of the ADA guidelines had to do with placement and accessibility. Some dyads used numerical analysis to calculate the details of their design informed by the ADA.

In addition to concerns for physical limitations, the students considered aesthetics, physical placement of their design, costs, and manufacturability. These constraints both guided and limited their designs. One student, Riley, commented, “Now, we want to make it aesthetically attractive.” All of the dyads discussed placement of their design solution relative to the nursing home facility. Some of the students were also aware of costs and verbalized it. However, costs were not brought up until after the students were further into the design process. Caleb mentioned, “I mean, it doesn’t say, but we could probably also think about cost, because they’re going to want to go for the price that is not going to break the bank.” The students used terms that were common among all dyads, such as “costs” and “expensive.” Two of the students also mentioned the manufacturability, “it just seems easier to manufacture to me” and maintenance of their designs, “As long as we got the right tension, you can put it [belt] back on pretty easily.” Although the students mentioned multiple interconnected variables, with the exception of the tenants’ physical disabilities, the students did not make frequent references to these variables.

## Optimization

Optimization is the iterative balancing of trade-offs to meet multiple conflicting requirements or constraints through optimization (Brophy, et al., 2008; Cross, 2002; Silk & Schunn, 2008). These trade-offs may include the competition of performance versus cost, robustness versus social constraints, and time versus environmental impacts. All dyads acknowledged the trade-offs they encountered in the design challenge. The only explicit constraint for the window design challenge was the inability to use an electrical outlet. Hence, two of the dyads mentioned other sources of electrical energy, solar and battery. However, the one dyad decided against solar energy due to costs. The other dyad implemented battery power without a solution for recharging them. Three of the dyads mentioned the trade-off between technical functionality and costs.

- Caleb      They're going to want to go for the price that is not going to break the bank.
- Taylor     Yeah.
- Caleb      [Our idea] defeats the purpose.
- Taylor     But they last forever. So we need something that lasts more than [we need] something that saves costs.

The students also attempted to balance functionality with aesthetics. Another dyad of students was sketching their design on engineering paper and realized the design was going to obstruct the window:

- Riley      We could put a pulley here. There could be a hook in the wall and just have the pulley up there; then we could do the crank down here.
- Dustin     Yeah.
- Riley      The question is, just how to fit that in without blocking the window too much?
- Dustin     See the crank doesn't actually have to go [on the bottom].
- Riley      Put it to the side that's true.

- Dustin To the side would probably be better than [the bottom]. [The bottom] would probably be too low.
- Riley That's true and you don't want a rope going across the window.
- Dustin Yeah as much as you can avoid, because you kind of, it has to be pulled upward. There are things like see-through fishing line that you don't notice. Is there stuff like that?
- Riley Yeah that's true. That wouldn't be strong enough though.
- Dustin No, I mean there are things like that. I don't know what might be strong enough.
- Riley Oh, yeah. It makes sense.

After this dyad decided to go with a transparent cord, it eventually became part of their final design.

Trade-offs were made on technical variables and non-technical variables as well. Although each dyad had conflicting ideas between themselves, three of the dyads were more verbal about resolving their conflicting ideas. Each student had to yield (trade-off) in some way to the greater good of the dyad's design. These verbalizations were not confrontational, but rather constructively conflicting and even included some friendly banter.

- Robert I like your design. Well the thing about mine is that it still requires all sorts of energy. Whereas, yours really minimizes effort.
- Ryan I don't know about this one.
- Robert I think I could make all of mine actually. I think yours could work too. I don't know [if] this is where we try to combine some of our stuff. Is there anything of yours you want to combine with mine?
- Ryan No.
- Robert We'll just have to drop yours then - just kidding. I really like my accordion one, but I just don't know if I can say...

All of the students recognized the need to optimize their design through optimization and it usually came through iteratively revisiting their design.

## **Unbounded Solution Paths**

Engineering design does not have a canned solution or a singular solution path. Rather engineering designs generally have multiple solutions and varying solution paths (Brophy, et al., 2008; Eide, et al., 2002; Foster, et al., 2001). There is not typically one best answer. Although distinct designs may approach convergence, the process of arriving at the final design may have been sought through unique paths. The students were not asked to brainstorm or develop multiple solutions. Yet, all of the dyads considered multiple distinct solutions. Most of the solution generation took place as brainstorming towards the beginning of the design process. However, some of the dyads considered divergent solutions as their ideas developed later in the process.

There were a total of 14 distinct design solution ideas among all dyads with ( $M = 4.17$ ,  $SEM = 0.54$ ) and ranging from two to six ideas per dyad. All dyads considered a pulley system in their design. Four of the dyads implemented pulleys in their final design. At least two dyads considered each of the following ideas: pump, lever, lubricant, wedge, jack, and ratcheting system. Table 9 represents the different design solutions mentioned during the design process. Although each dyad was unique in their solution and solution path, each dyad developed a final solution through iteratively analyzing and evaluating. All of the dyads' solution concept maps are included in Appendix I.

## **Sketching**

Katehi et al. (2009) suggest sketching can help students improve systems thinking. Sketching was the primary activity in which the students of this study engaged.

Every dyad spent the majority of their design time sketching. The students were provided with engineering paper, pencils, pens, and erasers. However, the students did not have access to drafting software for this design challenge.

Table 9

*Design Solutions by Dyad*

Solution	Dyad A	Dyad B	Dyad C	Dyad D	Dyad E	Dyad F
Pulley	X	X	X	X	X	X
Ratchet	X					X
Jack	X					X
Wedge	X	X				
Lube			X			X
Lever	X				X	
Cords		X				
Belt		X				
Wheels			X			
Rack			X			
Crank				X		
Pump					X	X
Bar					X	
Solar						X

The students in this research used sketching in a multiplicity of ways; such as developing a visual dialogue or to communicate ideas among one another.

- Eugene I just had a thought about what we could have done to make it better. [moves toward drawing] You could have put two of these [pointing to the pulleys on the sketch] and make this [gesturing the crank expanding] wider and put one of them there and one of them there [points to drawing where pulleys will be placed] so that we need only one of the cranks. But... it doesn't matter 'cause we're done. [Pause] Let's see if we can sketch that in.
- Skylar So you're saying...

- Eugene So, just make this [crank] a little wider. Draw another piece onto it like that [sketches addition to the crank] for the other ropes so that we only have to have one crank. See what I mean there?
- Skylar So we only need one?
- Eugene No, so when we twist it this way [gestures hand turning a crank] it opens up.
- Skylar Oh yeah.
- Eugene And then we twist it back the other way.
- Skylar I like it. I like it a lot!

Eugene attempted to explain his new idea through gesture and references to the sketch.

However, it was not until Eugene actually sketched his idea that he was able to elaborate and communicate it to Skylar.

Table 10 is a list of uses for sketching that may be applied to engineering design.

Table 10

*Sketching in Design*

Author	Item
Plimmer (2002)	Reduce cognitive load
	Creates a visual dialogue
Anning (1997)	Envision artifacts or structures
	Formulate or record plans
	Communicate intentions
Fraser & Henmi (1994)	Draw existing phenomena or ideas
	Provide repository for future inspiration
	Generate ideas
	Develop ideas
	Discover and develop emerging projects
	Test and verify solutions
	Optimize designs

The students also used sketching to present their final design.

- Dustin Okay, so I would say draw that [crank].
- Riley That's about all of my sketching ability.

Dustin As you can see, I'm not doing much better.  
Riley Well, it's not the ability, just get the idea across.  
Dustin Yeah okay.

The students' primary use of sketching was to generate, develop, and optimize their designs. Figures 7 through 9 represent a sample of the progression of sketches drawn by Dyad C. Figure 7 represents Dyad C's first sketch page. The students even labeled the page "brainstorm." Underneath the title "solutions" they listed: simple machines, add bar, more grip, more force, redesign windows, and rubber wheels.

Figure 8 is a sketch that Dyad C drew to represent the connection of the window frames to the rack and pinion design solution. The details of the connector are sketched as well as its overall placement with the window.

Figure 9 is a sketched final design of Dyad C. This page has a mix between hard lines produced by a ruler and a supplemental sketch showing the details of the rack and pinion. The previous sketches were more fluid and open to change as it served the purpose of generating and developing ideas (MacDonald, et al., 2007). The final sketch was meant to describe Dyad C's final design. Although sketching was not anticipated to play a prominent role in the students' systems thinking, it was evident through each dyad's design process.

Sketching is an important facet of engineering design and systems. However, sketching is just part of a larger concept, graphical visualizations. Graphical visualizations may include sketching, notes, digital forms of drawings, renderings in more than one dimension, simulations, and any other type of visual representation of the mind. Engineering design in practice, in undergraduate engineering programs, and at the pre-engineering level all make use of graphical visualizations.

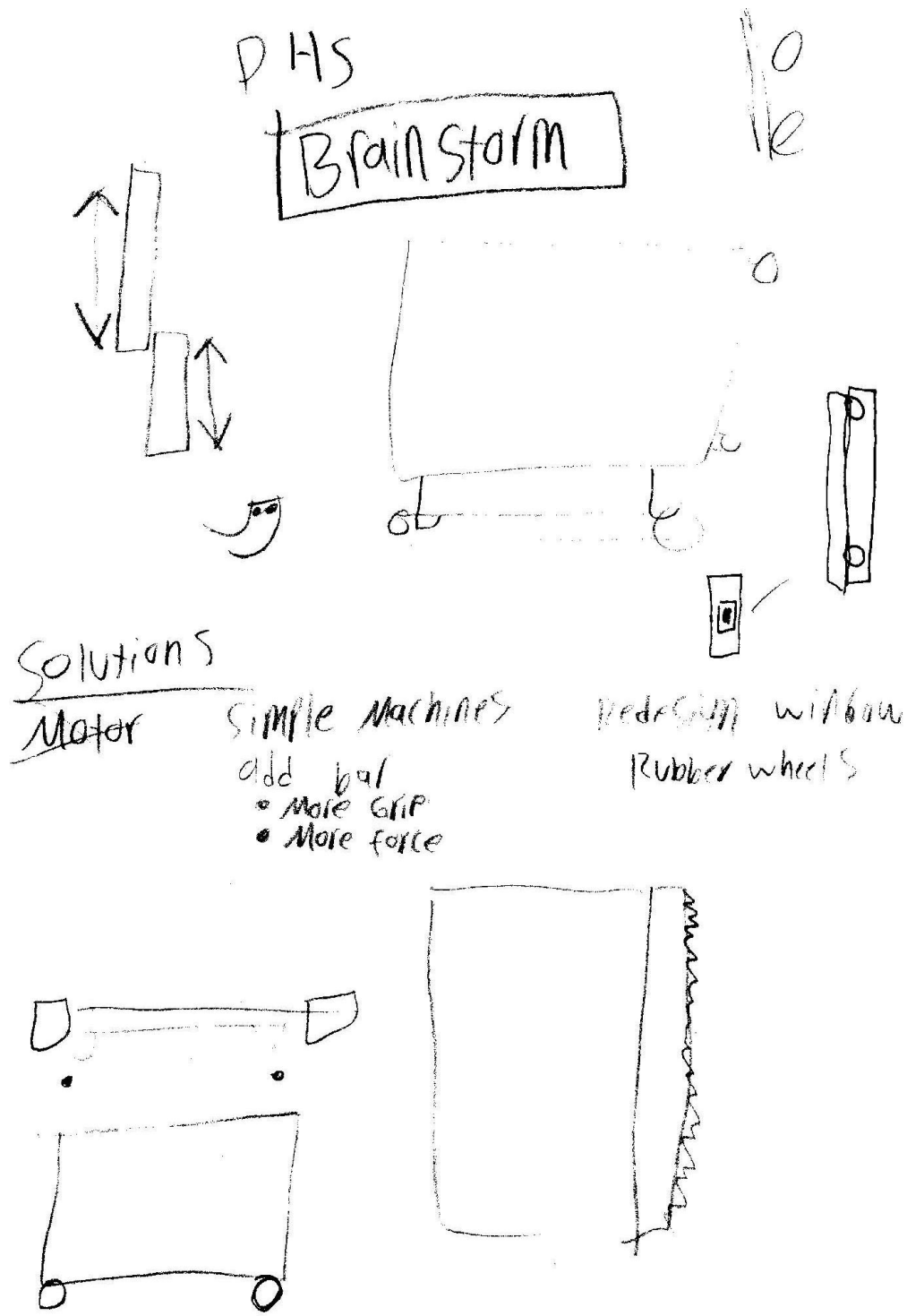


Figure 7. First page of sketching by Dyad C.



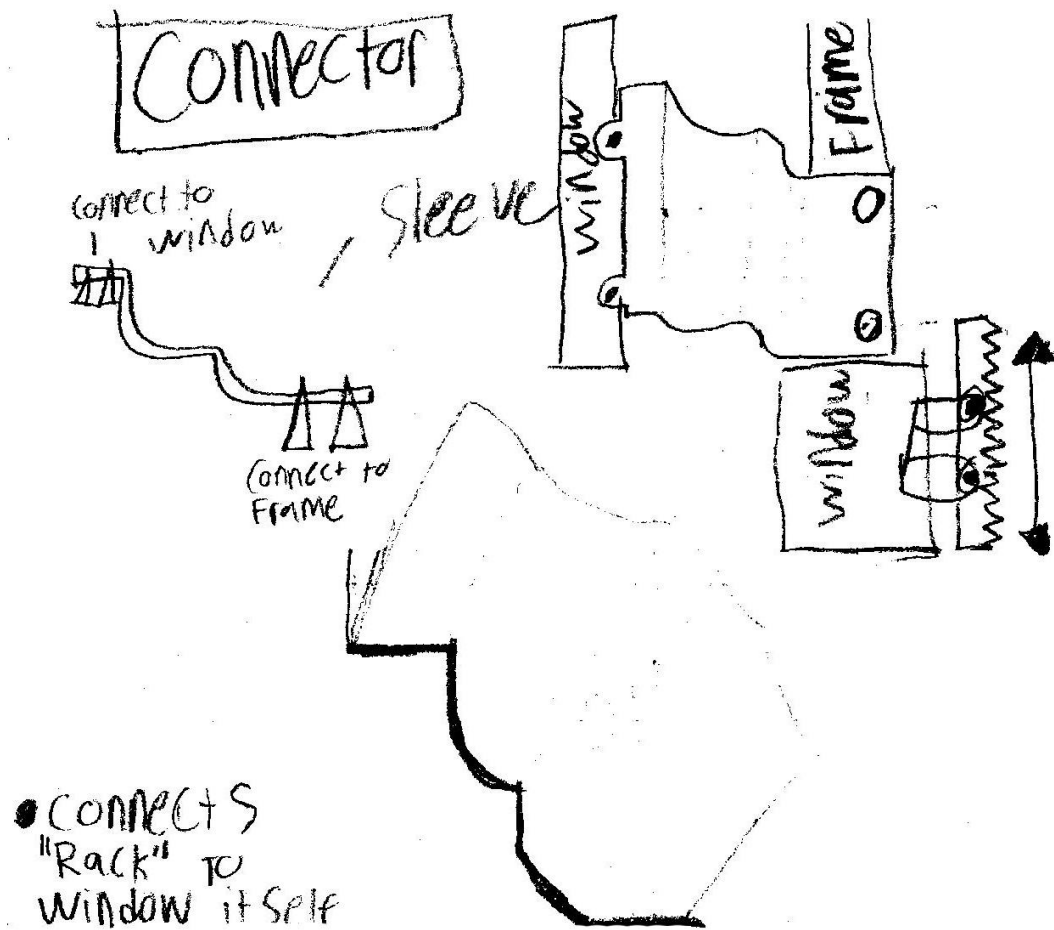


Figure 8. Sketch of window connection and rack and pinion placement by Dyad C.

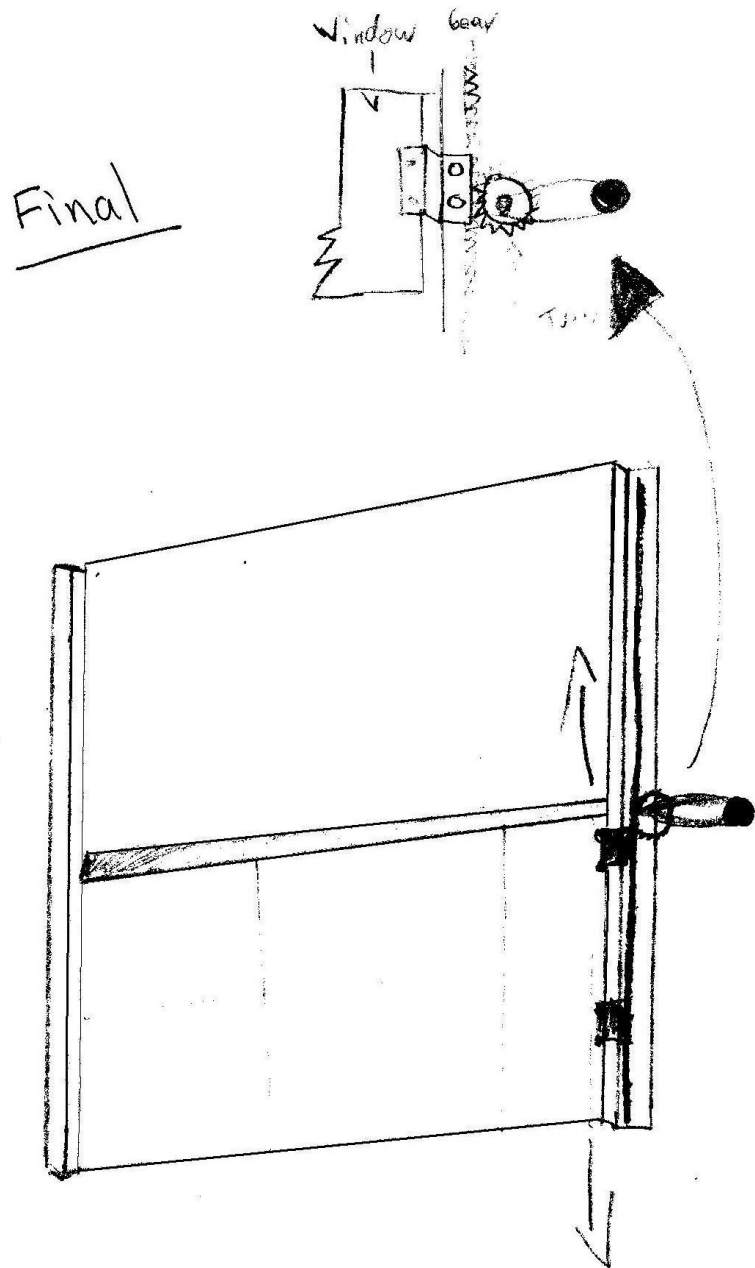


Figure 9. Final design sketch by Dyad C.

### **Analogical Reasoning**

Expert designers draw heavily from episodic memory and experience (Cross, 2004). Fler (2000) found that children ages three to five used their prior experience to design when they had no familiarity with the challenge. Analogical reasoning occurs when, “problems are solved by reference to previously-experienced situations and the lessons learned from them” (Kolodner, Gray, & Fasse, 2003, p. 120). Likewise, the students in this study drew from their experiences to aid in their design. However, the students did not have a depth of experience in window design or maintenance as would an expert. Therefore, the students used analogical reasoning to communicate among each other and develop their designs.

Analogies can have a positive, as well as a negative effect on student learning. If a fallacious analogy is chosen, the incorrect analogy can persist in the students’ understanding. Furthermore, if a student is not familiar with the given analogy, then the analogy might actually cause further confusion. There were instances when the students in Dyad F struggled to communicate their ideas to each other because they were not always familiar with each other’s analogies. Even with misunderstandings, the students persistently used analogies to communicate and understand their designs.

Table 11 is the list of analogies by dyad that the students verbalized. The dyads used a total of 38 analogies, of which 36 were unique. Dyad F contributed 45% ( $n = 17$ ) of the analogies, while Dyad D only drew upon one analogy. One student, Caleb, was cognizant of analogical reasoning and stated, “I can only put a simile to it like, uh, a windmill.” Analogies were used in brainstorming and developing ideas as well.

Table 11

*Analogies by Dyad*

Dyad	Analogy	Sum
A	Caulking Gun	7
	Carpentry	
	Jack	
	Pulley	
	Anchor Screw	
	Lever	
B	Bike Pump	5
	Fishing Line	
	Bullet Proof Vest	
	Transmission	
	Serpentine Belt	
C	Bike Chain	5
	Conveyor Belt	
	Towel Rack	
	Chair	
D	Holding Tank	1
	Steering Wheel	
E	Cup Holder	3
	House Door	
	Accordion	
F	Hose Reel	17
	Jack	
	Bike Pump	
	Trashcan Opener	
	Window Blinds	
	Foot Pedal	
	Foot Pump	
	Car Tire	
	Balloons	
	Pressure Gauge	
	Snow Board	
	Bindings	
	Tie wraps	
	Screw Driver	
	Bike Tire	
Exercise Bike		
Windmill		
Hydraulic Ram		
Crane		

### **Design Challenge Relevance**

Engineering design activities should be relevant to the students (Katehi, et al., 2009; Mehalik & Schunn, 2006; NAE, 2005). Relevance helps students make connections to their everyday doings, “We view design projects as helping to show the connections between science [or engineering, math, technology] concepts and solutions to real world problems” (Sadler, Coyle, & Schwartz, 2000, p. 303). The students in this study expressed engagement in this study during the design challenge and in the post-hoc focus group interview as well. After Robert and Ryan had finished sorting out what the objective and requirements for the design challenge were, Robert commented, “This is kind ‘a cool!” Robert and Ryan at the end of the design challenge discussed what they would name their final design and decided on “Double Hung Sash Opener 20000.” Dyad D carried on a similar conversation at the end of their design.

Eugene	What should we call it?
Skylar	The pulley system of death and destruction. How can we make the name of this device obscenely long?
Eugene	Um, we don't.
Skylar	Oh.
Eugene	How about, Team D's awesome project?

Dyad D chose to go with the more conservative name.

In the interviews, the students were asked about their experience with design the challenge. The following are some of their responses.

Robert	I learned that I could get inspiration out of nowhere when I had to start. I didn't think I had any ideas and then after just using the process, I guess just brainstorming and writing down dumb things, things came up that might work.
Taylor	It was fun!
Caleb	I like how it stimulated our minds. You know, it made you think and it made you find a solution that was good.

- Taylor     Yeah.
- Eugene    It had real life application; it wasn't just balled over in fairy land.
- Sean        It was interesting.
- Angel       It was kind of fun being at the center of finding out what would be the best way. It was kind of interesting.
- Dustin     It was a pretty interesting problem.
- Riley        Yeah, It was simple and everyday enough. [pause] I thought of my great grandma who actually died. In her later years she was mostly disabled. She could hardly walk, so like it would have helped her out a lot.

The students stated that the challenge was interesting, applicable, real life, and even fun.

The students also commented that they would have liked to have more experience with a sash window and the ability to use computer-aided drafting software.

### **Qualitative Summary**

Through the qualitative analysis, it was shown that the students demonstrated systems thinking. The systems themes were multiple interconnected variables, optimization, unboundedness, and sketching. The qualitative analysis also shed light on analogical reasoning and design challenge relevance. Although there were mentions of interconnected variables, the primary complex variable was that of the end user. The students optimized their design balancing trade-offs, both technical and non-technical constraints. All of the dyads generated multiple solution ideas. Sketching played an integral part in the students' design process. Sketching was used to generate, develop, and communicate their designs. The students also used analogies to better understand and develop their designs. Overall, the students commented favorably on the design challenge's relevance and interest.

## CHAPTER V

### DISCUSSIONS, IMPLICATIONS, AND RECOMMENDATIONS

#### **Research Rationale and Purposes**

A deeper and clearer understanding of students' habits of mind in engineering design would provide enhanced learning and teaching in engineering and technology education. Researchers have studied engineering design thinking, yet studies in systems thinking, with K-12 students are inadequate and poorly understood. Therefore, there is a need for research in systems cognition in engineering design at the K-12 level (Katehi, et al., 2009).

Cognitive issues are mental activities used during a design challenge while the processes are the ways in which the issues are approached. The purpose of this research was to understand the systems cognitive issues and processes used by high school students while engaged in collaborative engineering design challenges. The systems cognitive issues and processes were analyzed through the Function-Behavior-Structure cognitive analysis framework. Additionally, emerging themes and phenomena were analyzed qualitatively for systems thinking in engineering design.

This chapter discusses the findings from each research question. Following the discussions, implications for engineering and technology educators and researchers are proffered. The chapter will finish with recommendations for engineering and technology education researchers.

## Discussion

### Cognitive Issues in FBS – Research Question #1

The first research question asked what were the mental issues, activities, and operations used by high school students when attempting an engineering design challenge analyzed through the FBS framework. Once identified, the mental issues or activities were analyzed. Within the FBS framework there are six pre-defined cognitive components: requirements, function, expected behavior, structure, derived behavior, and documentation. In this section of the paper, each of the FBS cognitive activities and their analyses will be described and discussed.

**Structure.** Structure in the FBS framework constitutes the components of an object or system and their relationship to each other. Structures of an artifact or a system in design are the most visible and tend to receive the highest count of coded segments. The segments in this study were coded structure more often than any other FBS code. This held true for all dyads in that structure had the highest count of coded segments, ranging from 35 to 52% of coded utterances per dyad. Structures accounted for 43.8% of the total coded utterances. The following conversation between Bart and Ricky of Dyad A is demonstrative of how structures were so prevalent in coding. The resulting code is given in parentheses at the end of the sentence.

Bart	All right so we're going have a little lever system (S) so it's going to be like a car jack (Be) so it's going to have the base little ball right there (S) all right and those will be able to bend (Be) and it will be like an anchor screw (Be)
------	--



so you put it into the wall (S)  
 and it will bend (Be)  
 and it will latch up (Bs)  
 and it will just push it up (Bs)  
 so then we'll have something like this in there (S)  
 this will have a little latch for the window (S)  
 and this will actually go underneath the window (S)  
 so like you have your window here (S)  
 and little part (S)  
 and then we just drill it in there (S)  
 and we can put a pole inside there (S)  
 Ricky Yeah and then you just like... (O)  
 Bart And then we can remove this part right here (S)  
 that way this can slide up (S)  
 yeah dude all right and this is connected to spring device right here (S)  
 a pole with latches on it (S)  
 and it has a spring device (S)  
 and then after it will have the little jack right here (S)

After Bart began to explain his idea of a lever, he moved into an analogy of a car jack and an anchor screw. With the beginnings of the structure presented, Bart further explained the associated expected and derived behaviors: bending, latching, and pushing up. From that point on Bart continued with the placement of the lever system with its accompanying components and structures, while glossing over his team member's input. This excerpt, with structures accounting for 70% of the coding, was not uncommon. These lengthy explanations describing an idea or set of ideas took part within most of the dyads' design processes. In general, verbal protocol analysis segments (new thoughts) often begin with the words "and" and "so." Bart's dialogue above is an excellent example of this.

Although this research is not a comparison study, other's research findings inform the results of this study and their interpretations. In other FBS studies, structures had the highest frequency count (Hmelo-Silver, et al., 2000; Hmelo-Silver & Pfeffer, 2004; Kan

& Gero, 2009, 2010). This research attempted to use the same FBS framework used in Gero's studies. In three studies of designers performed by Gero and colleagues, the number of segments coded as structures were 33.9, 34.2, and 37.1% (Kan & Gero, 2010). Using the same window design challenge as this research study, Gero found one dyad of freshman engineering students had 42.6% of their segments coded structures. For all practical purposes, the resulting segments coded as structures were nearly the same as those of the freshman engineering students in Gero's current research. Additionally, Hmelo-Silver and Pfeffer (2004) have shown that the number of segments coded as structures may be similar among novices and experts alike. The resulting coding for structures in this study is not anomalous, as would be the case if structures were not the prevalent coding of segments. Therefore, structure was the dominant cognitive activity of the high school students in this research study.

**Expected behavior.** The assumed actions or characteristics of a design, what it does or could do are termed expected behaviors. Taylor and Caleb of Dyad F discussed their ideas and tried to balance the constraint of both raising and lowering the window with one device. Caleb proffered an expected behavior, combining both of their solutions, "Really, we could incorporate both of our ideas. 'Cause I mean, how is it going to stick?" When students brainstormed ideas, those were also coded expected behavior. However, if the students actually used that idea in the final design, it was coded a structure. Financial references were typically coded expected behavior if they were not specified as a design requirement or derived from the structure.

Expected behavior was coded overall at 26.6%. Additionally, expected behavior was the second highest code for five dyads. The range of percentages for expected behavior for each dyad was 22.7 to 33.8%. Expected behaviors were coded frequently as students brought up ideas of what the structure should do, made analogies, or made conjectures. In the design process, designers often think of an idea or behavior before the idea or behavior materializes into a structure. Gero and Kan found in their research that three designers used expected behaviors at 16.7, 5.3, and 17.3 %. The college engineering students used expected behaviors at 12.9%. Unlike the findings in this study, Gero and Kan found that expected behaviors were coded less often than derived behaviors in their research. The high school students in this study demonstrated novice characteristics in spending a large portion of their time conceptualizing the problem and in educating themselves. Whereas, experienced designers place more effort in developing, analyzing, and evaluating solutions.

**Derived behavior.** When behavior was taken from a structure, usually through analysis, it was coded derived behavior. Derived behaviors were only coded if the students described a behavior that was deduced or inferred from a structure. That is not to say that there had to be a segment coded structure before every derived behavior coding; for not every thought is verbalized. Furthermore, a derived behavior is often noted as a result of analysis from a structure. Below is an example of the interplay between structure and derived behavior.

Riley	That would be good if you could put in a crank or something (S) to help them. Yeah! (F)
Dustin	But, I'm not sure how you'd get that to work? (Bs)

I mean, you'd have to slide something under this bottom part (S)  
and then have it crank (Be)  
and the crank would raise the window (F)  
but pushing it up, probably. (Bs)

Riley proposed using a crank (structure) to help the tenants raise the window (function).

Dustin questioned (or analyzed – derived behavior) how a crank would be used in raising a window. Yet, Dustin allays his own concern by introducing a device (structure) that slides underneath the bottom of the window. With this device, the crank could then be turned (expected behavior) to raise the window (function). Dustin analyzed how the window would be raised by or through the device working in tandem with the crank. This analysis (derived behavior) was only possible after the device (structure) was introduced.

Derived behavior was coded 16.6% overall. The range of derived behavior for the dyads was between 3.6% and 25.4%. Derived behavior varied greatly by dyad. Dyad C and D had only 3.6 and 6.6% derived behavior. These two dyads also had the highest amount of segments coded structure. These results would suggest that the students focused more on the surface structures and not the underlying behaviors. Furthermore, these results suggest that fewer analyses were performed, as the transition from structure to derived behavior represents analysis in Gero's FBS framework. In Gero's study of college engineering students' derived behavior was coded at 30.1%. Although the results from derived behavior vary greatly between dyads, they suggest that the students in this study spent less cognitive effort describing the underpinnings and behaviors of the design structure.

**Documentation.** Documentation was only coded if the students verbalized the process of sketching or annotating. The coding scheme used for research question #1 and

#2 did not take into account the full experience of sketching and annotation.

Documentation was coded 9.3% overall. The range was 5.7 to 13.3%. Documentation was most prevalent in the last quarter of the design challenges. See Figure 10.

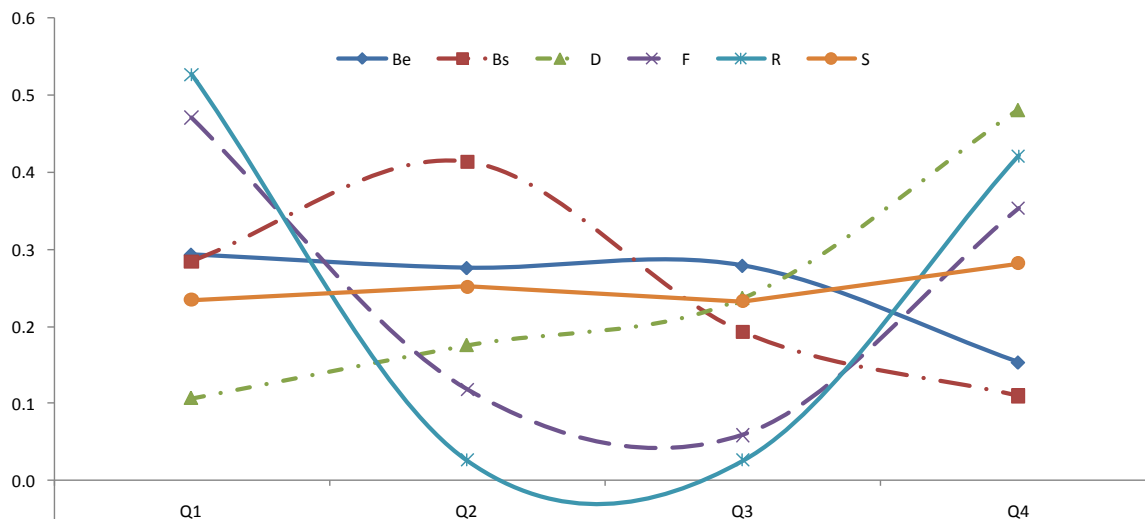


Figure 10. Code distribution over time for all dyads combined. The time, X-axis, was distributed over four quarters. The Y-axis is the proportion of time for each code per quarter. For example, Bs had roughly .3, .4, .2, .1 for quarters 1 to 4 respectively totaling 1.0. Note: Be = Expected behavior, Bs = Derived behavior, D = Documentation, F = Function, R = Requirements, S = Structure.

Towards the end of the dyads' design challenge they produced and discussed their final sketches. The sketching moved from idea generation and development to idea representation and description (MacDonald, et al., 2007). Essentially, the students finished their design challenge making final drawings rather than developing ideas.

The level of detail of sketching varied among dyads. Dyad A produced a final drawing that bordered intelligibility. Other dyads produced orthographic drawings showing various views of the design drawing. Some dyads even sketched exploded views to show the details of their designs. Sketching played a prominent role in the students'

design process and will be explored more fully in the later section of this chapter as a qualitative theme.

**Requirements and function.** Function and requirement are closely tied together and had similar coding results throughout the students' designs. Function is the purpose of the design. Requirements are the constraints set forth by the customer. In this study, the requirements were given through the window design brief. Function was only coded if the students referred to the overall purpose of the design, not a specific device, e.g. raising or lowering a window with greater ease. Requirements were coded if the students made explicit references to the design constraints or the design brief itself. The difference between function and requirements is that requirements are set by the client. It may seem that these codes tend to overlap. However, in context these codes can be distinct. An example will be given for clarification. A client might ask designers to produce a wheelchair for a disabled child. However, the designers may look beyond the requirement and see the problem and function as mobility and accessibility. Therefore, the designers may approach the solution through a mobility vehicle, an infrastructure change such as a ramp or elevator, or even a change in procedures or processes, as in the extreme example of the American with Disabilities Act.

Function and requirements in this study were coded overall 1.4 and 2.4%, respectively. The ranges for function and requirements were 0.4 to 2.9% and 0.7 to 4.9%, respectively. Gero's findings for college students were 1.8 and 2.5% for function and requirements respectively. Figure 10 shows that both function and requirements were primarily present in the beginning and end of the design process. The dyads reviewed the

requirements and functions in the beginning to frame the problem. The students referred back to these codes towards the end of the challenge to evaluate them against their designs. Below is an example of how Robert and Ryan tried to frame and define the problem towards the beginning of the challenge.

Robert     Okay, but oh, but the problem it said was... (R)  
 Ryan        Raise and lower. (R)  
 Robert     Trying to raise and lower [the window]. (R)  
 Ryan        Oh yeah. I thought we were only trying to overcome gravity here.  
               (R)  
 Robert     We're trying to do lots of stuff! (F)

In this excerpt the dyad was trying to understand the functions from the requirements. Overall, the students did not frequently mention function or requirements. This could be due in part to the design challenge not having an excess of stated requirements. Regardless, the results of coded function and behavior segments in this study do not vary greatly from other studies using the FBS framework.

**Summary of FBS cognitive issues.** The students in this study showed evidence of systems thinking through the FBS framework. The students primarily addressed structures in their design. Yet, the students addressed the expected and derived behaviors of their design. Compared to the literature, the students in this study had a higher proportion of expected behavior. Additionally, the students were not able to do a redesign, test, evaluate in this design challenge. If the students had that opportunity to do these activities, the distribution of FBS codes might have varied (Hmelo-Silver, et al., 2000).

## Cognitive Processes in FBS – Research Question #2

Research question #2 questioned what mental processes, approaches, and transitions were present when high school students attempted an engineering design challenge analyzed through the FBS framework. The transition from one FBS code to another has meaning and is practically significant. For example, the coding may frequently transition between certain coded pairs. Through analysis, one may find that a code may also serve as a pivot point between other codes.

**FBS transitions.** As shown in Figure 2, Gero has labeled the transitions between certain codes to describe the design process (Gero & Kannengiesser, 2004). There are four principle transitions, with further derivations of formulation. These transitions include formulation ( $F \rightarrow Be$ ), synthesis ( $Be \rightarrow S$ ), analysis ( $S \rightarrow Bs$ ) and evaluation ( $Bs \leftrightarrow Be$ ). For example, formulation ( $F \rightarrow Be$ ) occurs when the designer postulates how a function is to be met through an anticipated action. One student described how the window could open more easily (function) by reducing the friction (expected behavior) between the window sash and the frame. Transitions in FBS are explained more fully in Gero's (1990) initial paper on the FBS framework.

The total numbers of transitions for all dyads that are relevant to Gero's FBS framework are listed in Table 12. FBS relevant transitions comprised 60.3% of the total transitions. Reformulation I ( $S \rightarrow S$ ) had the highest percentage, 37%. This result is congruent with the raw counts of coded segments and the measures of centrality. As novices, the students focused primarily on structures.



Table 12

*Function-Behavior-Structure Transitions for All Dyads Combined*

Process	<i>M</i>	<i>SEM</i>	%
Reformulation I (S→S)	37.00	4.73	36.69%
Reformulation II (S→Be)	17.50	1.95	17.36%
Synthesis (Be→S)	16.00	1.83	15.87%
Evaluation (Be↔Bs)	14.00	2.92	13.88%
Analysis (S→Bs)	11.33	4.70	11.24%
Documentation (S→D)	3.83	1.92	3.80%
Reformulation III (S→F)	0.50	0.34	0.50%
Formulation (F→Be)	0.50	0.34	0.50%

The next grouping included reformulation II (S → Be), synthesis (Be → S), evaluation (Be ↔ Bs), and analysis (S → Bs), 17, 16, 14, 11%, respectively. These activities, synthesizing, evaluating, and analyzing, require higher cognitive efforts. The following example is illustrative.

Taylor    Is there a way to use the drum pedal (S)  
               to crank it? (Be)  
 Caleb     Thinking about that (S)  
               [moves hand to chin]  
               I mean application wise, it would be a lot more complicated. (Bs)

Taylor questioned how a drum pedal, one of the brainstormed ideas, could be used in a system to move a sash window up and down. Taylor reformulated the structure (pedal) into an expected behavior (cranking). Caleb muses on how the pedal (structure) could be applied and deems (derived behavior) through his unspoken mental analysis that it would be a complicated design.

The bottom group included documentation ( $S \rightarrow D$ ), reformulation III ( $S \rightarrow F$ ), and formulation ( $F \rightarrow Be$ ) at 4, 0.5, 0.5% respectively. Documentation was low as it only counted if documentation came after structure. In the design challenges, documentation came after many other codes besides structure. The other two transitions were low as they included function. Function was only coded in a handful of instances.

**Measures of centrality.** To further understand the transitions, measures of centrality were calculated and analyzed. OutDegree was calculated from the number of transitions and links leaving each FBS code. Betweenness measured how often a code was in the middle of a transition from one code to another. A snippet of a conversation among Dyad B demonstrates the betweenness of structure.

Dustin	I can't think of anything other than sprockets and bike chains. (Be)
Riley	And cars, they use them [chains], but it's basically the same thing, just heavy duty . (Be)
	That's the thing! Do we want to make it a giant sprocket? (S)
	Let's see how big the small one would be first. Okay? (S)
Dustin	So, the small one. You probably want to do it, um... (S)
Riley	You don't want to have this huge gear over there . (Bs)
Dustin	No, so three inches. (S)

Dustin and Riley were brainstorming ideas (expected behavior) about sprocket and chains and how they were analogically (expected behavior) used in a car. Riley conceives using a sprocket (structure). Both Riley and Dustin move to discuss the size of the sprocket (structure). Riley interjects that the size cannot be too large for aesthetic reasons (derived behavior from the placement near the window). Structure was used to go between Be and Bs and then out of Bs. Betweenness implies that a code, such as structure in the example above, plays a pivotal role in cognitive transitions. The last measure of centrality

calculated and analyzed was closeness. Closeness is the distance in links from one code to another. This measure suggests that if a code is topographically close to other codes it will have frequent transitional activity.

The raw count of OutDegree was highest for structure. This finding parallels the number of segments coded structure in research question #1. There was a high percentage of segments coded structure, hence there was a high percentage of transitions from structure to other codes. Structure tended to transition into itself as the students described their ideas, see Table 13. Bart's monologue of a lever system, previously mentioned in an earlier section, is a clear example of structure transitioning to structure.

Table 13

*Mean Centrality Values for All Dyads Combined*

FBS Code	Degree		Betweenness		Closeness	
	<i>M</i>	<i>SEM</i>	<i>M</i>	<i>SEM</i>	<i>M</i>	<i>SEM</i>
Be	5.33	0.33	3.53	0.97	0.16	0.01
S	4.50	0.34	3.58	0.88	0.17	0.01
Bs	4.17	0.31	1.28	0.63	0.15	0.01
D	4.00	0.37	1.64	0.66	0.15	0.01
R	2.67	0.42	1.14	0.85	0.12	0.01
F	1.50	0.22	0.17	0.17	0.12	0.01

*Note.* Be = Expected behavior, Bs = Derived behavior, D = Documentation, F = Function, R = Requirements, S = Structure.

Although structure had the highest OutDegree raw count, expected behavior had the highest OutDegree value. The OutDegree value was generated not only from the number of links (connections to other codes), but from the number of transitions to other

codes as well. Expected behavior also shared the highest values for betweenness and closeness. Expected behavior served as the primary transition point between codes.

Structure was also pivotal in cognitive transitions. The results from the measures of centrality placed expected behavior and structure in the top tier of codes. The next grouping included derived behavior and documentation. The bottom tier included requirements and function. The final group, requirements and function, had distinctly lower centrality values when compared to other groups.

**Cognitive processes summary.** Generally, transitions from requirements and function codes took place at the beginning and end of the design challenge. There were a few dyads that had no segments coded requirements or function during the middle half of their design challenges. These results could suggest that the students understood the purpose of their design challenge. This design challenge did not include a “laundry list” of constraints. Rather, the challenge was purposefully left open-ended for relevance and design complexity. The results could also suggest that the students became consumed with their designs and did not explicitly refer back to the purposes of the design challenge. However, all dyads completed the design challenge with deference to the given constraints.

The students in this study focused heavily on transitions involving structures. The students also used higher order cognitive skills such as analysis, evaluation, and synthesis, but to a smaller extent. Congruent with the other analyses in this study, structure was widely used in transitions. Additionally, expected behavior played a pivotal

role when transitioning between codes. Also congruent with the previous analyses in this research, the codes function and requirements received infrequent attention in transitions.

### **Systems Cognitive Themes and Phenomena**

Research question #3 sought to identify emerging qualitative themes and phenomena as they related to systems thinking in engineering design. Furthermore, if there were themes or phenomena, how could these themes and phenomena be analyzed and interpreted? There were six systems and engineering themes that emerged: multiple interconnected variables, optimization, unboundedness, sketching, analogical reasoning, and relevance. This section will discuss and attempt to interpret these themes.

**Interconnected variables.** The students considered multiple variables related to their designs. Not only were each dyad's design solution complicated with multiple interacting parts, they were complex. They were complex in that the designs included variables outside the technical design solutions. The primary variable referenced by the students was accessibility. This was followed by aesthetics, physical placement of the design solution, cost, maintenance, and manufacturability. Accessibility was frequently referenced as a design constraint among all dyads. Perhaps the students were able to relate to nursing homes and other facilities and had an idea of the end user. One of the students, Riley, even remarked how his design "would have helped her [his deceased great grandmother] out a lot" in her later years. The students not only made general mention of assistive constraints, they specifically considered arthritis, wheelchairs, and other ergonomic factors. Furthermore, the students in this study belonged to the

generation raised while the Americans with Disabilities Act (ADA) was effected and implemented. Although the impact cannot be easily measured, the ADA has had at least indirect, if not direct, impacts on the students' ways of thinking. Furthermore, other research have successfully implemented assistive themes in engineering education (Carlson & Sullivan, 1999; Coyle, Jamieson, & Oakes, 2005).

The students also mentioned physical placement of their design solution. Some dyads considered aesthetics in the design and its placement. Again, aesthetics could be considered another constraint in reference to the nursing home tenants. There were other variables that were only briefly mentioned. These included costs, manufacturability, and maintenance. The latter two were only mentioned once. Perhaps this is due largely to the scope of the design challenge. If the design challenge had actually included production and testing of a prototype, the students would have likely considered a wider spectrum of variables. The students' lack of addressing multiple and diverse constraints does not imply that they are incapable of balancing them in their designs. The students successfully recognized and designed to the nursing home tenants' needs and constraints.

**Design optimization.** The students optimized their designs seeking to balance competing constraints. The students had to make trade-offs between technical functionality and either costs or aesthetics. What appeared to be trade-offs often led to an improved design. Examples included the rope being traded for a transparent high strength cord and the ergonomic placement of a manual crank by Dyad B. From the concept maps generated by the researcher of the students' design it may be deduced that the students were continually reevaluating and improving their designs.

Within the dyads the students had to balance the competing ideas among themselves. Each dyad had positive conflict resolution. The conflict often led to better or improved ideas. Dyad A consisted of a boisterous, outspoken senior, Bart, and a reserved junior, Ricky. There were many instances when Ricky's suggestions appeared to be ignored. However, Ricky persisted and was eventually able to implement his ideas in the design. For example, early in the design challenge Ricky suggested the idea of a large push button. It was not until much later in the design that Ricky was able to see his idea considered. Eventually, Dyad A was able to implement the push button into their final design. This small conflict did not create contention. As a matter of fact, when the design challenge began to wind down, the one turned to the other and said, "We're a great team dude!"

All the dyads in this research study iteratively optimized their design solutions. The students showed signs of optimizing throughout the design challenge. If the students had further expertise vis a vis a sash window and its construction, perhaps they would have recognized the number of competing constraints that surrounded this problem.

**Unbounded design.** Engineering designs may be approached through multiple solution paths with varying end products. The students in this research investigated alternatives and even variations on their final design. Altogether, the students generated 14 possible design solutions. Not every dyad contributed an equal amount. Dyad F generated six unique ideas while Dyad D produced two. Interestingly, these same dyads represented the top and bottom of the range for analogies generated, 17 and 1, respectively.

All of the dyads considered a pulley system in their design; with four dyads using pulleys as part of their final design solution. It is not certain why pulleys were so prevalent. Their instructor was consulted on this finding. He stated that pulleys did not receive more attention than other topics in the curriculum. Even though the students' designs converged on pulleys, the students considered other design alternatives and compared them to each other. Robert and Ryan were a prime example as they wrestled back and forth about which of their four main ideas they would use. They finally decided upon a solution that blended their distinct ideas. Other dyads similarly combined the ideas they generated to produce a final solution. These students demonstrated that they can generate and compare alternative ideas.

**Graphical visualizations.** Sketching and annotation were used by all students throughout the engineering design challenge. Sketching is helpful when understanding and analyzing a system. For example, Dustin had just suggested the idea of a crank. He recognized that there was a challenge in using a crank to move the window up and down. So, his teammate Riley attempted to tackle the problem.

Riley      Well, what I was thinking... you could... and this is a little complicated.  
Dustin     Okay, we just have to draw it out.

After Riley struggled to articulate his ideas, Dustin realized that sketching their design would be helpful.

Sketching was not just limited to offloading cognitive effort, it was used to generate, develop, and communicate designs. Dyad C applied sketches and list making to brainstorm their ideas, see Figure 8. Sketching was also applied to develop and optimize



the students' designs. Sketching was further employed to communicate ideas and designs to each other and the "client." Sketching was the primary tool, physically and cognitively, exploited by the students. Albeit, the computer was used for information gathering and concept verification, the depth and breadth of the use of sketching was vast in the students' design process. The results of this study are congruent with the literature in that graphical visualization plays an important role in engineering design (Anning, 1997; Katehi, et al., 2009; MacDonald, et al., 2007). Therefore, educators might do well to use sketching and other graphical visualizations more thoroughly in their curriculum.

**Analogies.** The students also used analogies to communicate to each other and to themselves regarding their ideas. Analogies were used to develop a design as well. The number of analogies used was 38. Without much experience in window or assistive design, the students drew upon their experiences through analogies. In the post-hoc focus group, the students were asked how they generated different ideas.

Taylor	We tried finding examples. We used a screw driver, a crane, blinds, car jack. [We] just tried finding things that we already used.
Caleb	Me and my dad go around the house – projects – we mess with stuff like that. [We] never had to mess with windows, though we have sliding windows that push up. I also got my ideas from a snow boarder binding system.

These students were explicit about drawing from their episodic memory. However, analogies do have limitations. It is possible that a fallacious analogy could be used incorrectly and in turn propagates misconceptions. Additionally, not all students have the same background or experience. Hence, an analogy that works for one student may be completely irrelevant to another. In spite of the limitations analogies pose, their use with students should be capitalized.

**Authentic and relevant.** Students tend to be more engaged in a design activity if it is perceived to be relevant and it pertains to the student's everyday life (Brophy, et al., 2008; Sadler, et al., 2000; Svensson & Ingerman, 2010). Overall, the students favorably spoke of the design challenge's relevance. Their comments included, "cool," "fun," and "interesting." The design challenge also "had real life application" that pertained to the students. Some of the students took ownership in their designs by spontaneously naming them. The design challenge scope was not overly restraining and was simple and clear enough for the students to understand (Sadler, et al., 2000).

The findings from this study demonstrated that high school students are capable of systems thinking in an engineering design challenge. The students' systems thinking was demonstrated through FBS analysis and complexity themes alike. Although the high school students focused primarily on structures, they also referenced behaviors. From the analysis of the measures of centrality, it was found that expected behavior played a pivotal role in the students' cognitive transitions. These results suggest that the students looked beyond the façade of their design and delved into its anatomy and operation.

Engineering design is by definition rarely performed in isolation; isolation from other designs, networks, systems, or humans. Dym et al. (2005) went as far to say that all design is systems design. If systems are so pervasive in engineering design, then what is to be taught that is unique to systems thinking and how will it be delivered? Foster et al. (2001) have been able to successfully include complexity thinking in their undergraduate engineering curriculum. However, can systems thinking be taught to high school, or even K-8 students? Jacobson and Wilensky (2006) claimed that students can learn to think in

terms of complexity. The findings from this research study have shown that high school students can think in terms of systems. However, this research does not claim to know how this capability was developed.

### **Implications for Engineering and Technology Educators**

This study is limited in that the participants were students from one pre-engineering program. Therefore, the reader is encouraged to reflect on how the findings from this study may be applicable to their unique situation. From the results of this study, engineering and technology teachers may infer that systems thinking may be learned by students as it relates to the FBS framework and other phenomena. That is not to say that the instructors and students alike have to be trained in all of the details and nuances of Gero's FBS framework. Although the nomenclature of FBS may not need to be taught, the underlying concepts and thinking of the FBS framework could lend to enhanced systems thinking (Hmelo-Silver, et al., 2000; Katehi, et al., 2009).

Structures constituted the dominant cognitive activity in this study. Expert designers have also relied heavily on structures in previous studies (Gero & Kan, 2009; Kan & Gero, 2008). Experts often considered and employed functions and behaviors to create their designs as well. Therefore, students should be encouraged to go beyond the structures of a device or system while designing. The students did not receive explicit training in systems thinking, let alone in the FBS framework. Nevertheless, the students in this study were also able to consider behaviors, particularly when transitioning from one thought to another. Expected behavior was pivotal in the students' cognitive

processes. Hence, educators might spend more effort helping students when developing their designs.

Curriculum and pedagogy with systems thinking could help the students discover the purposes (function) of a device and explore how those purposes are achieved (behavior). For example, when investigating and learning about pulleys, the teleological aspects could be addressed. The teleology may include mechanical advantage, hoisting, or rappelling. The purposes could also be made contextual, ranging from an assistive window opener to cranes or even mountaineering. Relevant behaviors such as securing a load, reducing friction, and providing an ergonomic feel may be examined as well.

In addition to discussing and teaching functions and behaviors, interconnectedness of variables can be explored. The students from this study were able to consider multiple variables and also noted that these variables interacted within the design. For example, one dyad realized that a manual crank was not aesthetically attractive below the window. Moving the crank to the side of the window not only created a more attractive design, but also allowed for one less pulley and easier access for the tenants. The results of this study do not suggest that students will address all germane variables, as maintenance and manufacturability were only addressed by two separate students. Recently graduated engineers in industry are not expected to know all of the pertinent variables that affect a design. Even an experienced and expert engineer has to frame the problem. What then is to be expected of high school student in engineering design with regard to multiple interconnected variables? Clearly, students will not be able to identify and design for all variables. However, the students should be taught that there

are multiple factors in a design that likely interact. Furthermore, instructors could instruct the students that among all the variables there are those which are salient and those which are not.

An example of a systems design challenge with multiple interconnected variables is that in which students have to design a “green” residential house. The students must balance the competing constraints of a robust design with cost and time. The design challenge also requires that the house be livable. The home owners’ experience cannot be ignored. Additionally, there are multiple technical disciplines involved ranging from structural analysis to thermal conduction and solar technology to dynamic energy consumption. This challenge covers a wide range of expertise that high school students, let alone a single professional, could not fully comprehend. Therefore, the students need instruction on how to consider and analyze these variables.

Quite noteworthy was the finding that all students consistently recognized the human variable in their designs. Perhaps the design problem was sufficiently pertinent such that the students could relate to and visualize it. Many of the students commented on how interesting the design challenge was to them. These students had no experience with window design or maintenance and were vaguely familiar with intricacies involved. Yet, the students have all used a window before; albeit, not sash windows. Considering these points, the students were able to some degree relate to or imagine the end user’s perspective. After Dyad A had decided on an initial design, they began to further visualize their design.

Ricky      If they’re too old to even push down on it, they can just lean on it.  
Bart        Yeah.

Ricky     And if they get bored...  
Bart       Lean on it.  
Ricky     If they fall asleep, guess what? They'll open the window a little bit too.  
Bart       Okay. I want to take this a little bit further. This window is not safe for elderly use.

The students are not only capable of including the human factor in their design, but they should be encouraged to extend to other non-technical variables as well (NAE, 2004).

The students engaged in sketching throughout the entire design process, with an increase toward the end of the design challenge. Students should consider the use of sketching to not only communicate ideas, but to generate, develop, and optimize ideas and designs as well. The sketching does not have to be precise or expert. As Riley stated, "it's not the ability, just get the idea across." Too often sketching is merely used to communicate ideas (MacDonald, et al., 2007). Yet, research has shown that drawing is integral in engineering design (Bucciarelli, 1994). Not all educational activities need a formal assessment. Sketches to aid in design could be assessed formatively without a grade assigned. Teachers may also want to increase how often sketching is performed.

Sketching is not only helpful in design; it likewise assists the students in systems thinking. The abstractness and looseness of sketching allows for adaptation and divergence. Furthermore, the sketch can offload the cognitive stresses related to complexity. Sketching is not limited to a pencil and paper drawings. There is an array of multimedia tools available to students in design. This research did not allow students to use computer aided drafting tools. Results from previous research were mixed in regard to the use of computer aided drafting (Denson, et al., 2010).

All of the students in this study considered multiple alternatives in the design challenge. The curriculum in the pre-engineering program included the use of the decision matrices. However, not one team used an annotated decision matrix in their analysis. Educators should carefully consider how to instruct students on developing design alternatives and how to make informed decisions regarding such. Perhaps the underlying principle is continuous improvement. Optimization, iteration, and evaluation of competing constraints have the end of an optimal design. There are many models of continuous improvement in industry such as Total Quality Management and Six Sigma from which instructors may draw.

Educators should help students draw from their own experience when designing. Analogical reasoning can help the students understand the many abstract science and math concepts in engineering. Analogical reasoning is often used in engineering design and should be included in engineering design curriculum and instruction (Christensen & Schunn, 2007).

Systems thinking is an important concept in engineering design (Asunda & Hill, 2007; Brophy, et al., 2008; Dym, et al., 2005; Katehi, et al., 2009; Mehalik & Schunn, 2006). The implications for systems thinking are expansive and broad. This study was able to focus on a portion of systems thinking, particularly through the lens of the FBS framework. The implications for educators include focusing on deeper concepts and behaviors, multiple variables and their interactions, optimization, sketching, and analogical reasoning. Most salient is the finding that students in this study were capable of thinking in terms of systems.

### **Recommendations for Engineering and Technology Education Researchers**

This triangulated mixed methods research study is a viable approach for studying student thinking in terms of systems. Although there were limitations with this study, all of the data sources combined to recreate the students' design process and shed light on the students' system thinking. Hence, qualitative and quantitative themes emerged through the use of triangulated data coupled with analysis in the FBS framework.

This research attempted to collect data in an environment close to the students' everyday classroom settings. The students worked with peers in their engineering classroom while working at their computer workstations. The students were aware that they were being audio and video recorded along with their computer movements. However, when asked in the interview, the students stated that the recording equipment was not imposing or distracting. Additionally, the researcher in this study did not hover over the students. The students were accustomed to working in teams and rarely sought help. The researcher was always present for any questions, yet the researcher purposefully moved to the other end of the room from the students. The students were aware and took advantage of the freedom to move about the room. The environment where data is collected is important as it affects the students' context and attitudes as well as research validity. As a researcher, small efforts to accommodate the study participants may yield more trustworthy and valid results.

As this research was emerging, it could provide a spring board to additional research studies. The research could include a larger sample of students from diverse schools using distinct engineering curriculum. Qualitatively, different schools and



different pre-engineering programs could be included. Undoubtedly, students from other pre-engineering curricula would have unique language, techniques, and themes.

Quantitatively, a larger sample size, would yield a higher statistical power. Additionally, a larger sample size would also allow for inferential statistics to be computed and analyzed. The range of students studied could also be stratified by year in school and academic performance. Questions to be answered could include how do seniors in high school differ from freshman? How do non-engineering students in high school compare to pre-engineering students?

This study could also inform experimental research that investigates system thinking interventions. Systems thinking is not unique to engineering design. Other studies outside of engineering might also benefit from the FBS framework and other systems perspective.

Other perspectives and frameworks of engineering design could be investigated, such as collaboration, creativity, and the use of the computer for sketching and information gathering. The scope of the design challenge could also be expanded by allowing the students to build, test, evaluate, and redesign. Furthermore, the study of systems thinking could be expanded along the novice to expert continuum.

Currently, John Gero and this researcher are comparing the high school student results with second year engineering students from a large university. This comparison will seek to inform a larger study funded by a proposal. In this proposal, a larger sample size will be chosen that includes students from diverse schools. Analyses such as

Markov, entropy, and linkography that have been used in Gero's previous research will be employed.

To enhance and simplify the research process, small technical changes could be implemented. Instead of using one small audio recorder between the students, the individual students could have their own audio recorder with a lapel microphone. However, if the students had to wear a microphone, they might find it more unnatural. Another video recording device could have been used to more readily capture the students while sketching. Once again, the placement of an overhead video recorder might be imposing. These latter improvements might be helpful, but they would only ease in the analysis, not necessarily provide new data.

The students in this research were able to show thinking in terms of systems. This assertion was derived by analyzing the students' activities while working an engineering design challenge. It is hoped that this research not only provides insight to researchers in engineering and technology education, but to educational practitioners as well.

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APPENDICES



Appendix A  
IRB Approval



Institutional Review Board  
9530 Old Main Hill, Suite 214  
Logan, UT 84322-9530  
Telephone: (435) 797-1821  
Fax: (435) 797-3769



3/9/2010

USU Assurance: FWA#00003308

Protocol # 2555

SPO #: ESI-0426421

AES #: UTA00

## MEMORANDUM

TO: Kurt Becker  
Matthew Lammi

FROM: Kim Corbin-Lewis, IRB Chair *Kim Corbin-Lewis*  
True M. Fox, IRB Administrator *True M. Fox*

SUBJECT: Systems Thinking of High School Students in Engineering Design

Your proposal has been reviewed by the Institutional Review Board and is approved under expedite procedure #7

- There is no more than minimal risk to the subjects.  
There is greater than minimal risk to the subjects.

This approval applies only to the proposal currently on file for the period of one year. If your study extends beyond this approval period, you must contact this office to request an annual review of this research. Any change affecting human subjects must be approved by the Board prior to implementation. Injuries or any unanticipated problems involving risk to subjects or to others must be reported immediately to the Chair of the Institutional Review Board.

Prior to involving human subjects, properly executed informed consent must be obtained from each subject or from an authorized representative, and documentation of informed consent must be kept on file for at least three years after the project ends. Each subject must be furnished with a copy of the informed consent document for their personal records.

The research activities listed below are expedited from IRB review based on the Department of Health and Human Services (DHHS) regulations for the protection of human research subjects, 45 CFR Part 46, as amended to include provisions of the Federal Policy for the Protection of Human Subjects, November 9, 1998.

Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

Appendix B  
Letter of Consent



Department of Engineering & Technology Education  
6000 Old Main Hill  
Logan, UT 84322-6000  
Voice: (435) 797-1496



Date Created: January 26, 2010; Page 1 of 3  
USU IRB Original Approval: 02/XX/2010  
Approval terminates: 02/XX/2011  
Protocol Number: XXXX  
IRB Password Protected per IRB Coordinator

## **PARENT PERMISSION**

### **High School Students Systems Thinking in Engineering Design**

**Introduction** Dr. Kurt Becker and Matthew Lammi of Utah State University (USU) would like your permission to allow your student to participate in a research study of systems thinking in engineering design. In school, your student is learning about engineering and this study may help researchers understand high school students' systems thinking about engineering.

**Procedures** If you give permission for your student to participate s/he will be expected to complete a short demographic survey at the beginning of the study. Students will be identified with an ID number on the survey. Students will design a window opening mechanism in a team, followed by an interview by Dr. Becker or Mr. Lammi. The interview will take approximately 30 minutes. Students may be contacted via phone by a member of the research staff to verify researcher interpretations. While students are designing a window opening mechanism as a team, they will be asked to wear an audio recorder and microphone. Also, design sessions will be video-taped and interviews will be audio recorded. The computer movements will also be tracked. The total time commitment is expected to be 2-3 hours.

**Risks** There is minimal risk in participating in this study. Your student's participation will not impact his/her class grade.

**Benefits** This research may benefit both the field of engineering and technology education and your school district. The field may benefit by shedding additional light on systems thinking and experience during an engineering design challenge. The school district may benefit through receiving knowledge of the impact of engineering courses on students.

**Payment/Compensation** Your student will be paid \$10 for participating in this study.

**Voluntary nature of participation and right to withdraw without consequence**  
Participation in research is entirely voluntary. Your student may refuse to participate or withdraw at any time without consequence or loss of benefits.



Department of Engineering & Technology Education  
6000 Old Main Hill  
Logan, UT 84322-6000  
Voice: (435) 797-1496



Date Created: January 26, 2010; Page 2 of 3  
USU IRB Original Approval: 02/XX/2010  
Approval terminates: 02/XX/2011  
Protocol Number: XXXX  
IRB Password Protected per IRB Coordinator

**Confidentiality** Research records will be kept confidential, consistent with federal and state regulations. Only Dr. Kurt Becker and his team of researchers will have access to the data. To protect the privacy of your student, a random code number will replace the student's name on the data. Confidentiality will be maintained by keeping data on a password-protected computer and in a locked file cabinet in Dr. Becker's locked office at USU. The code will be kept separate from the data, also in a locked file cabinet. After the data have been gathered and the analysis is completed, the coding sheet linking the students to this study will be destroyed along with the audio and video recordings.

**IRB Approval Statement** The Institutional Review Board for the protection of human participants at USU has approved this research study. If you have any pertinent questions or concerns about your rights or a research-related injury, you may contact the IRB Administrator at (435) 797-0567 or email [irb@usu.edu](mailto:irb@usu.edu). If you have a concern or complaint about the research and you would like to contact someone other than the research team, you may contact the IRB Administrator to obtain information or to offer input.

**Copy of consent** You have been given two copies of this Parent Permission document. Please sign both copies and retain one copy for your files.

**Investigator Statement** "I certify that the research study has been explained to the individual, by me or my research staff, and that the individual understands the nature and purpose, the possible risks and benefits associated with taking part in this research study. Any questions that have been raised have been answered."

---

Kurt Becker, Ph.D.  
Principal Investigator  
[kurt.becker@usu.edu](mailto:kurt.becker@usu.edu)  
(435) 797-0213

---

Matthew Lammi  
Co-Principal Investigator  
[mdlammi@ieee.org](mailto:mdlammi@ieee.org)  
(435) 757-1267

By signing below I give permission for my son/daughter to participate in this research study.

\_\_\_\_\_  
\_\_\_\_\_  
Parent/Guardian signature

Date



Date Created: January 26, 2010; Page 3 of 3  
USU IRB Original Approval: 02/XX/2010  
Approval terminates: 02/XX/2011  
Protocol Number: XXXX  
IRB Password Protected per IRB Coordinator

Department of Engineering & Technology Education  
6000 Old Main Hill  
Logan, UT 84322-6000  
Voice: (435) 797-1496

**Youth Assent:** I understand that my parent/guardian is aware of this research study and that permission has been given for me to participate. I understand that it is up to me to participate even if my parents say yes. If I do not want to be in this study, I do not have to and no one will be upset if I don't want to participate or if I change my mind later and want to stop. I can ask any questions that I have about this study now or later. By signing below, I agree to participate.

\_\_\_\_\_  
\_\_\_\_\_

Student signature

Date

**Student Contact Information**

Name (Please Print): \_\_\_\_\_

Phone number: \_\_\_\_\_

Address: \_\_\_\_\_

\_\_\_\_\_

Appendix C

District and School Permission





To: John Haning  
Northridge High School  
2430 N. Hill Field Rd  
Layton, UT 84041  
[jhaning@dsmail.net](mailto:jhaning@dsmail.net)

From: Kurt Becker  
National Center for Engineering and Technology Education  
6000 Old Main Hill  
Utah State University  
(435) 797-0213  
(435) 797-2567 (fax)  
[kurt.becker@usu.edu](mailto:kurt.becker@usu.edu)

RE: Permission to advertise and use facility for a spring research project  
Date: 1/29/09

Greetings, The National Center for Engineering and Technology Education is studying how students work through the design process to understand systems thinking and improve educational pedagogy and teacher preparation.

The following pages in this document contain an advertisement agreement that will allow information regarding this project to be distributed to students in your school by their engineering and technology teacher. Students will then contact the researchers directly to enroll in the study. A review copy of the student/parent informed consent is included. A proposal detailing the merit, goals, and procedures is attached along with the design task, demographic questionnaire, and interview questions. Davis School District

would also like a letter of consent with the official school letterhead indicating that you are aware of and approve of the study.

Please allow us to address any concerns you may have regarding the study. We look forward to your positive response in support of this study to be conducted at your school during the spring of 2010.

Best Regards,

Kurt Becker, Ph.D.

Appendix D  
Demographic Questionnaire

## Demographic Questionnaire

Please answer the questions to the best of your ability. If you have any questions regarding this questionnaire, please ask the administrator.

1. Would you describe your race/ethnicity as:
  - A. Caucasian
  - B. Black, non-Hispanic
  - C. Latin American
  - D. Asian
  - E. Native American
  - F. Not mentioned here:
2. What is your age?
3. What is your gender?
4. What is your high school grade point average (GPA)?
5. What is your year in school as of Feb 15, 2010?
6. What is the highest level of education obtained by either of your parents/guardians?
  - A. Some High School
  - B. High School/GED
  - C. Some College
  - D. Associates Degree
  - E. Bachelors Degree
  - F. Masters Degree
  - G. Doctoral Degree
  - H. Other, Please Specify:
7. How would you describe your neighborhood?
  - A. Suburban
  - B. Rural
  - C. Urban
8. Please list the engineering courses have you taken?

Appendix E  
Window Design Challenge

### **Double-Hung (Sash) Window Opener**

Your design team has been approached by Warm Heart Estates, a local nursing home, to design a new product to assist its elderly residents.

The nursing home administrators have noticed that changes in humidity during the summer months cause the windows of the 65-year old building to “stick,” thus requiring significant amounts of force to raise and lower the window panes. The force required to adjust the windows is often much too large for the nursing home tenants, making it very difficult for them to regulate their room temperature.



**Your team has been tasked with designing a device that will assist the elderly tenants with raising and lowering the building’s windows. You will produce a complete engineering design solution for the client.** Someone should be able to build the device from your solution without any questions. Since each window is not guaranteed to be located near an electrical socket, this device should not rely on electric power.

The building’s windows are double-hung (as seen in the figure above). The double-hung window consists of an upper and lower sash that slide vertically in separate grooves in the side jambs. This type of window provides a maximum face opening for ventilation of one-half the total window area. Each sash is provided with springs, balances, or compression weather stripping to hold it in place in any location.

Your team has identified the following websites as potential sources of useful information:

“Double Hung Window Construction”

<http://www.oldhouseweb.com/how-to-advice/double-hung-window-construction.shtml>

“Double Hung Windows – Everything You Need to Know” (1 min. 34 sec.):

<http://www.youtube.com/watch?v=xW7OMHYI4kY>

American Disabilities Act (ADA) information:

<http://www.ada.gov/>

<http://www.ada.gov/pubs/adastatute08.htm> (full act, as amended in 1990)

[http://en.wikipedia.org/wiki/Americans\\_with\\_Disabilities\\_Act\\_of\\_1990](http://en.wikipedia.org/wiki/Americans_with_Disabilities_Act_of_1990)

ADA Accessibility Guidelines for Buildings and Facilities (ADAAG):

<http://www.access-board.gov/adaag/html/adaag.htm>

Appendix F

Semi-structured Post-hoc Focus Group Interview

Guiding Questions:

How did you define the problem?

How did you decide what information to get?

How did you develop or come across different ideas (solutions)?

How did you figure out the details to each potential solution?

How did you know which ideas would work and which would not work?

How did you compare ideas?

Why and how did you choose your final idea or plan?

How did you decide what to put in the proposal?

Did you have a plan for the design? If so, what was your plan?

Is there anything else you needed or wanted that would have helped you?

What did you like about this design experience? How could we make this design experience better?



Appendix G  
FBS Training Document

The following document was used to familiarize the coding analysts with the FBS framework. This will be used in conjunction with the journal articles, working groups, and practice coding the preliminary data.

*Working Definitions for the FBS Framework*

Code	Description
Function (F)	The purpose of what it is for or why
Requirements (R)	The requirements set forth by the customer
Expected Behavior (Be)	Behavioral expectations for the structure; what it does, or could do
Derived Behavior (Bs)	Behaviors derived or taken from the structure, usually through analysis
Structure (S)	Components of an object or system and their relationship; description of what it is
Documentation (D)	Annotations used during the design process
Other (O)	Utterances that are not related to design

- When brainstorming a concept: Be
  - If described as a component of the design: S
- When dealing with finances not specified as a constraint (requirement) or if not derived from the structure: Be
- If drawing analogies: Be
- If gathering information or educating themselves: O
- Count the two participants as 1 unit

“An approach to systems from artificial intelligence, called SBF theory (Goel & Chandrasekaran, 1989), provides some vocabulary for thinking about how to describe systems. In attempting to have the computer design and debug systems, Chandrasekaran and Goel discovered that a representation that highlights structures, functions, and behaviors of systems, and the connections between those parts, allows for effective reasoning.

- **Structure** refers to the physical structures of a system; for example, the lungs are a physical structure in the respiratory system and the alveoli are physical structures within the lungs.
- **Function** refers to the purpose of the system or subsystem. The respiratory system transports oxygen throughout the body to the organs that require it; the lungs extract oxygen from air.
- **Behavior** refers to the dynamic mechanisms and workings that allow the structures to carry out their function; that is, the mechanisms that cause changes in the structural state of a system.

The most accessible behaviors are the visible ones (e.g., air going in and out of the nose, the chest moving). But behavior is far more than what one can see (e.g., the invisible electrical impulses traveling through nerves that cause the respiratory system's involuntary movements). We can describe behaviors using a language of causality-some action causes some state enabling some other action. Understanding "invisible" and time-delayed causality is a big part of what makes behavior so difficult to understand. Because invisible and time-delayed causality are so difficult to understand (Feltovich et al., 1992),

behavior is the hardest aspect of systems to understand. Novices tend not to consider that a system has behavior until some anomaly in the normal function of a system arises and they have a need to debug or explain it (Murayama, 1994). Table 1 presents a simplified analysis of the respiratory system in SBF terms.”

**TABLE 1**  
**Simplified Structure-Behavior-Function Model of Respiratory System**

<i>Structure</i>	<i>Behavior</i>	<i>Function</i>
Lungs	Gas passes from high concentration to low across semipermeable membrane.	Bring in oxygen <i>for cells</i> , remove waste <i>from cells</i> .
Diaphragm	Lower pressure in chest by increasing volume.	Move <i>lungs</i> so they can take in fresh air.
Brain	Send signals <i>to respiratory system</i> . Receive and process <i>signals regarding body status</i> .	Control or regulate <i>movement of lungs in response to changing metabolic needs</i> .

*Note.* Italics indicate connections with other systems.

Hmelo-Silver, C. E., Holton, D. L., & Kolodner, J. L. (2000). Designing to learn about complex systems. *The Journal of the Learning Sciences*, 9(3), 247-298.

“The SBF framework allows effective reasoning about the functional and causal roles played by structural elements in a system by describing a system’s subcomponents, their purpose in the system, and the mechanisms that enable their functions. Goel et al. (1996) used SBF theory to model reasoning about a cooling device.

- More specifically, **structures** refer to elements of a system (e.g., fish, plants, and a filter are some of the elements that comprise an aquarium).
- **Behaviors** refer to how the structures of a system achieve their purpose. These are the interactions or mechanisms that yield a product, reaction, or outcome (e.g., filters remove waste by trapping large particles, absorbing chemicals, and converting ammonia into harmless chemicals).
- Finally, **functions** refer to why an element exists within a given system, that is, the purpose of an element in a system (e.g., the filter removes byproducts from the aquarium).

We define function contextually. The distinction between behavior and function can be confusing due to contextual issues. For example, from the perspective of an aquarium system, fish respiration is a behavior that releases waste products. If we were analyzing the fish as a system, we might consider respiration as a function and gas exchange and various cellular reactions as behaviors. Weld offered a similar analysis concerning the explanations of physical devices such as a car engine.”

Hmelo-Silver, C. E., & Pfeffer, M. G. (2004). Comparing expert and novice understanding of a complex system from the perspective of structures, behavior, and functions. *Cognitive Science*, 28(1), 127-138.

“The goal of designing is to transform a set of functions into a set of design descriptions (D).

The function (F) of a designed object is defined as its teleology.

The behavior (B) of that object is either derived (Bs) or expected (Be) from the structure.

Structure (S) is the components of an object and their relationships.

Example of requirements:

“quite important is its about the thermal-incli- inclis ( ) pen” (E1, 43)

“design a-a prototype” (E1, 56-57)

Examples of function:

“that’s the standard plain thermal paper err and then it can draw” (E1, 54)

Examples of expected behavior:

“either atoms or line types” (E1, 55)

“we can print thermo reactive dyes onto media substrates” (E1, 68)

Examples of behavior:

“it’ll be about fifty percent more expensive” (E1, 199)

“if you lift an optical mouse slightly off the page you’ll see the pattern it creates”

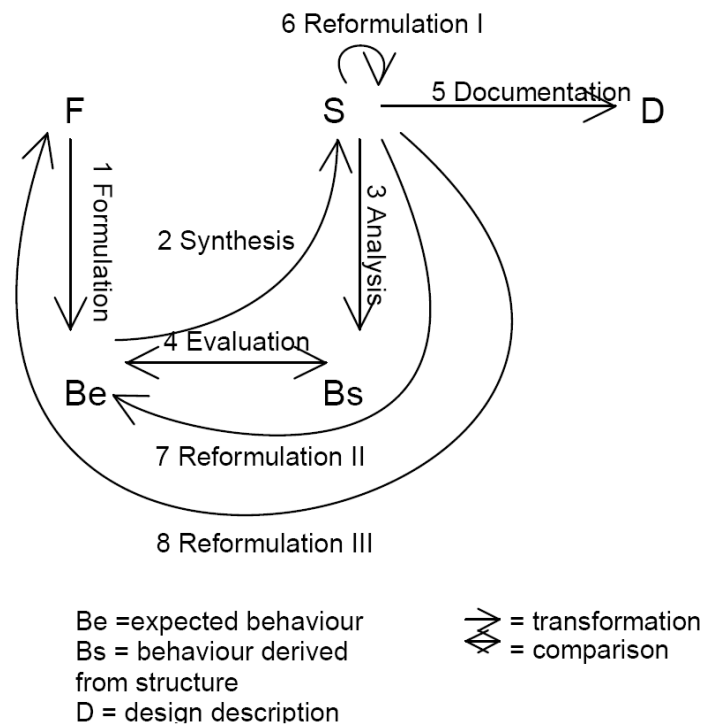
(E1, 672 674)

Examples of structure:

“a sledge or a snowboard- a skis or snowboard” (E1, 150)

“show the relative size of the pen if you’ve got an example” (E1, 171)”

Gero, J. S., & Kan, J. W. (2009). Using the FBS Ontology to capture semantic design information in design protocol studies. In J. McDonnell & P. Lloyd (Eds.), *About Designing: Analysing Design Meetings* (pp. 213-229): CRC Press.



- “Structure variables describe the components of the object and their relationship, i.e. *what it is*.”
- Function variables describe the teleology of the object, i.e. *what it is for*
- Behavior variables describe the attributes that are derived or expected to be derived from the structure variables of the object, i.e. *what it does*.”

Gero, J. S., & Kannengiesser, U. (2004). The situated function-behaviour-structure framework. *Design Studies*, 25(4), 373-391.

## Appendix H

### Measures of Centrality Equations



## Measures of Centrality Equations

$$\text{Degree} = \frac{\sum(c_{\max} - c(n_i))}{c_{\max}}$$

Where:

$c_{\max}$  = maximum degree value possible

$c(n_i)$  = degree centrality of node  $n_i$

$$\text{Closeness} =$$

Where:

$d$  = distance

$n_i$  = node of interest

$n_j$  = node to which closeness is being calculated

$$\text{Betweenness} = \frac{\sum_{j < k} (g_{jk}(n_i))}{g_{jk}}$$

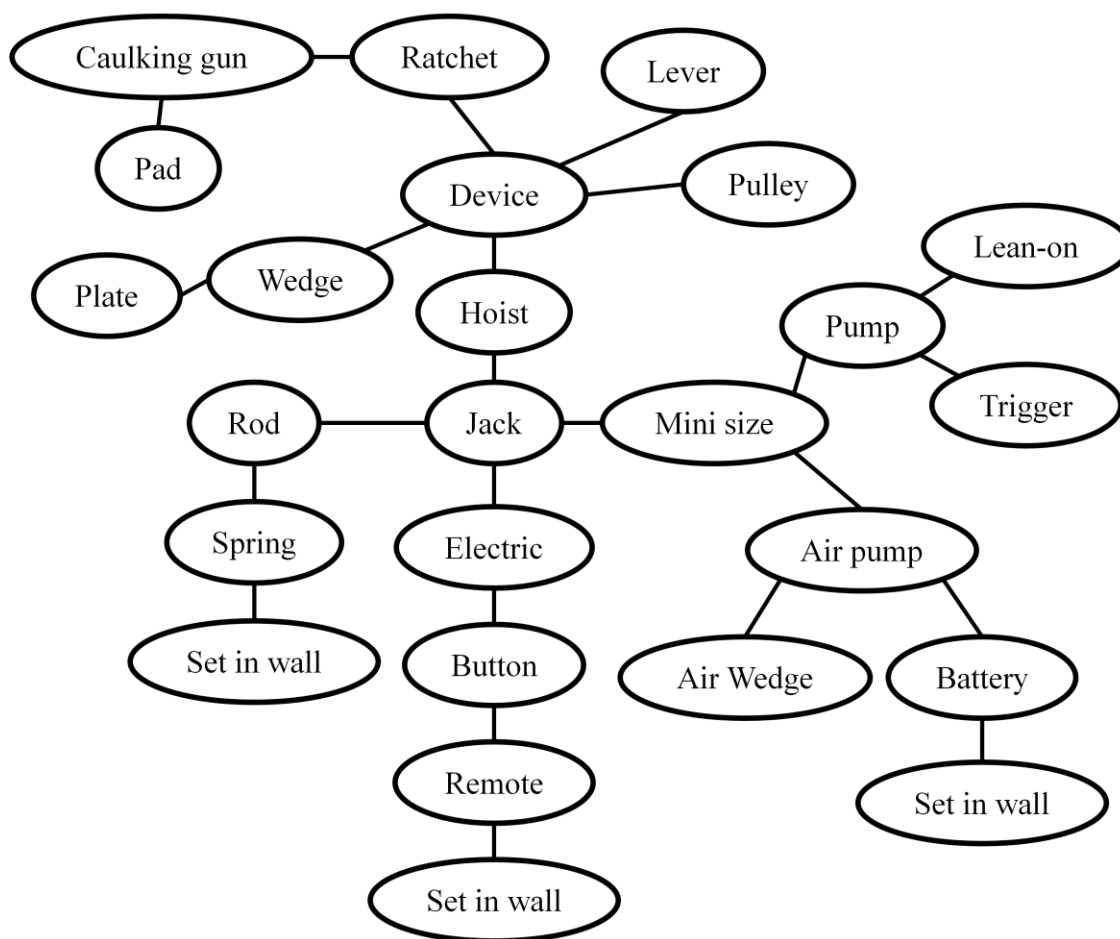
Where:

$g_{jk}(n_i)$  = where  $i$  is a node that is used to transition from  $j$  to  $k$

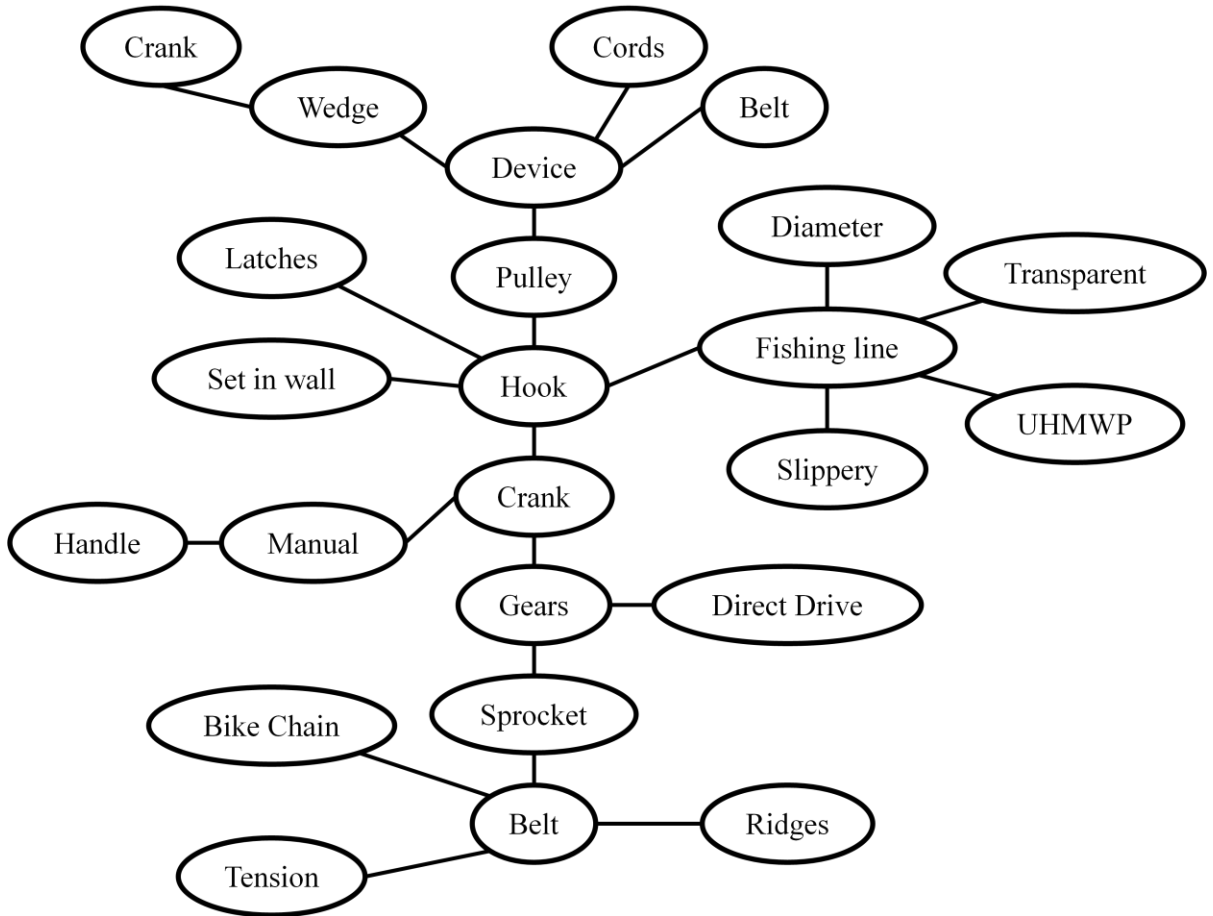
$n_i$  = node of interest

Appendix I  
Solution Concept Maps

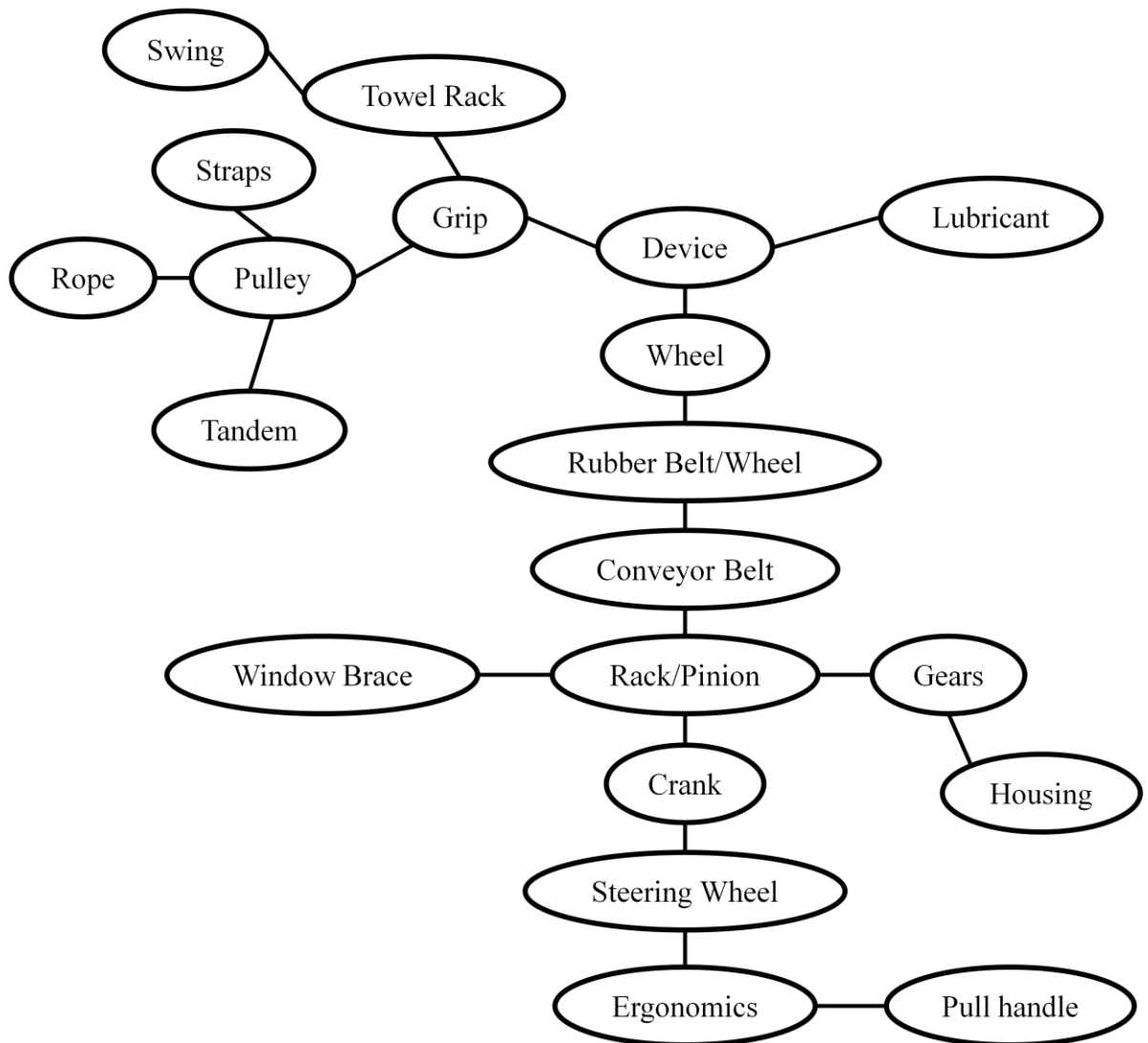
## Dyad A



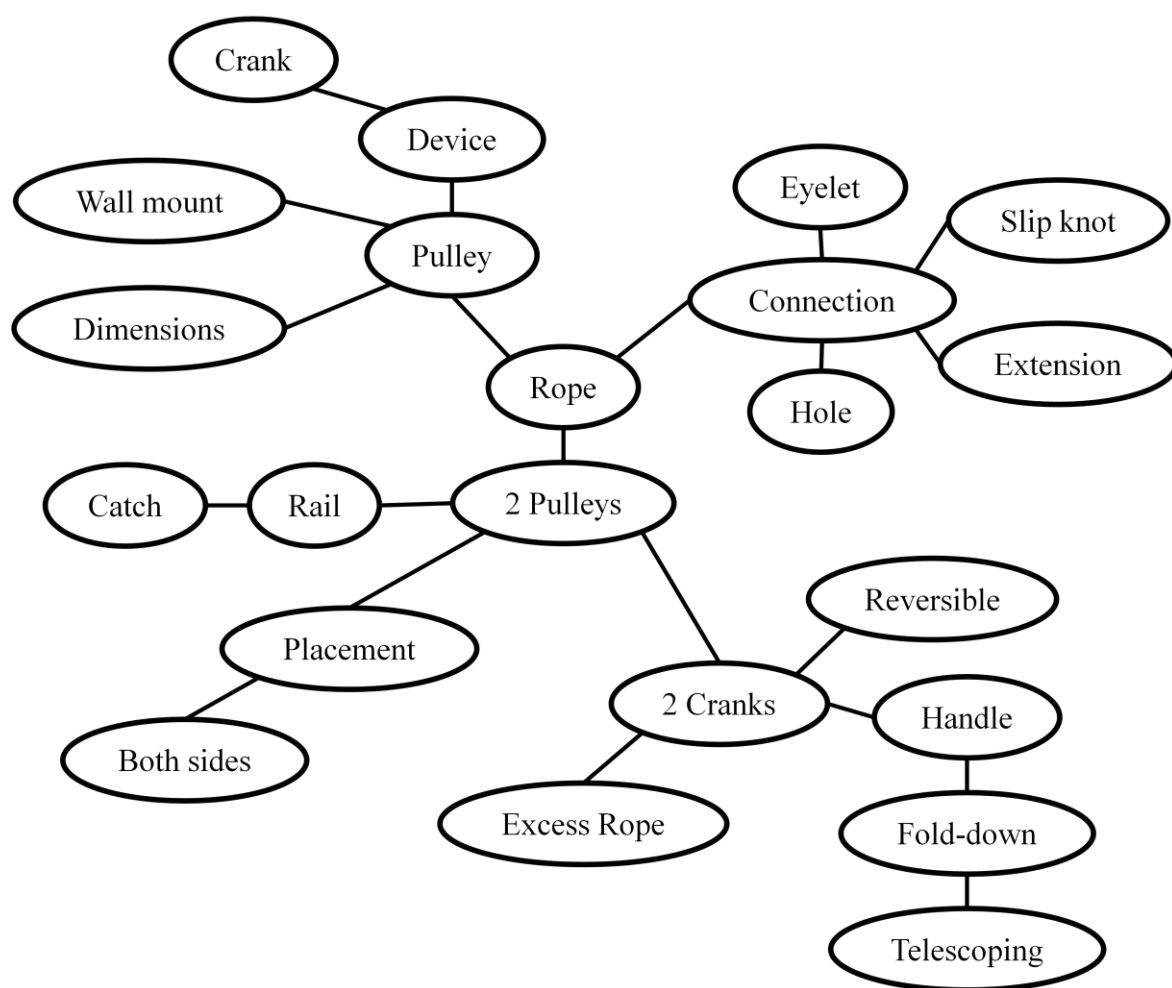
Dyad B



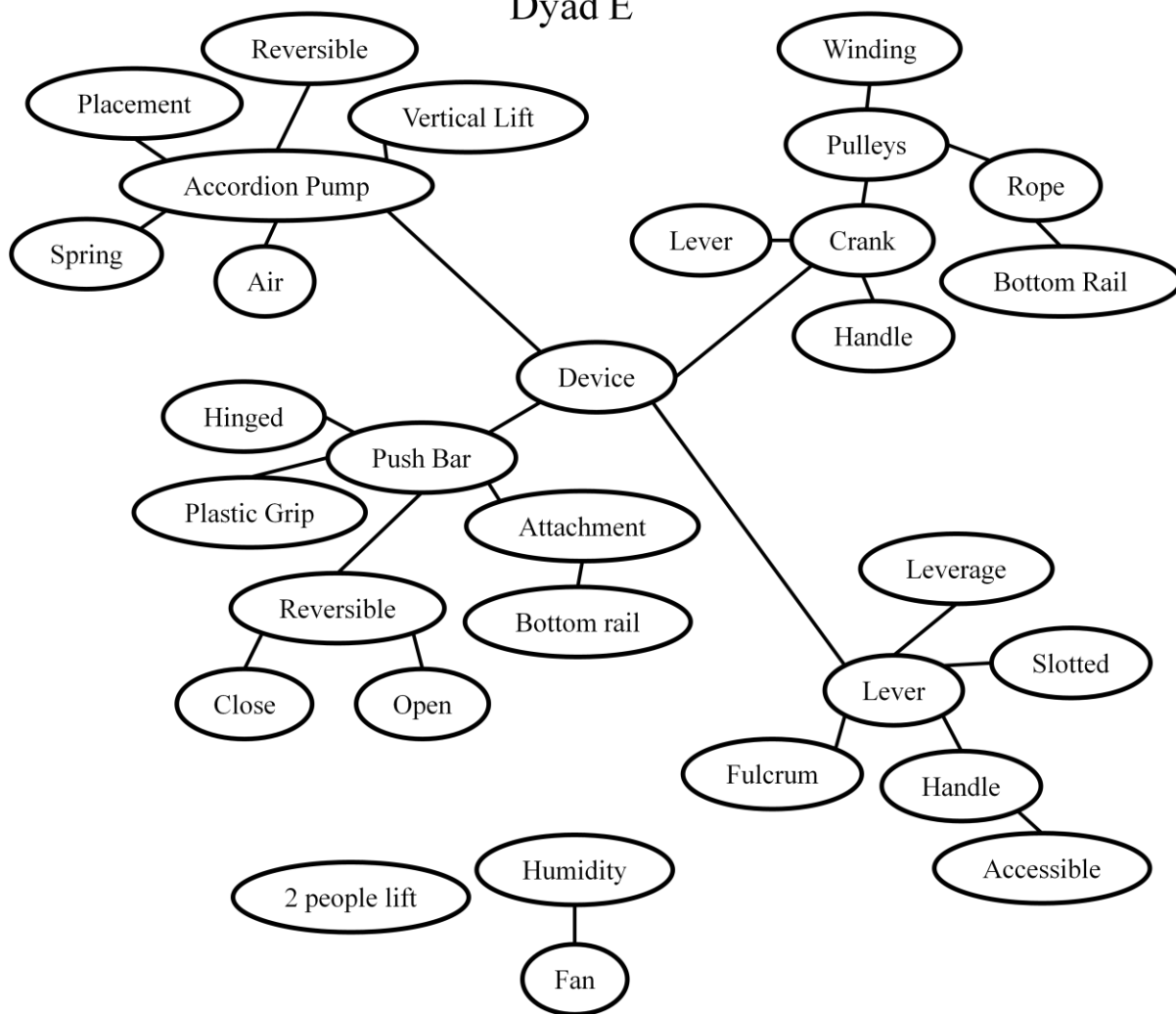
## Dyad C



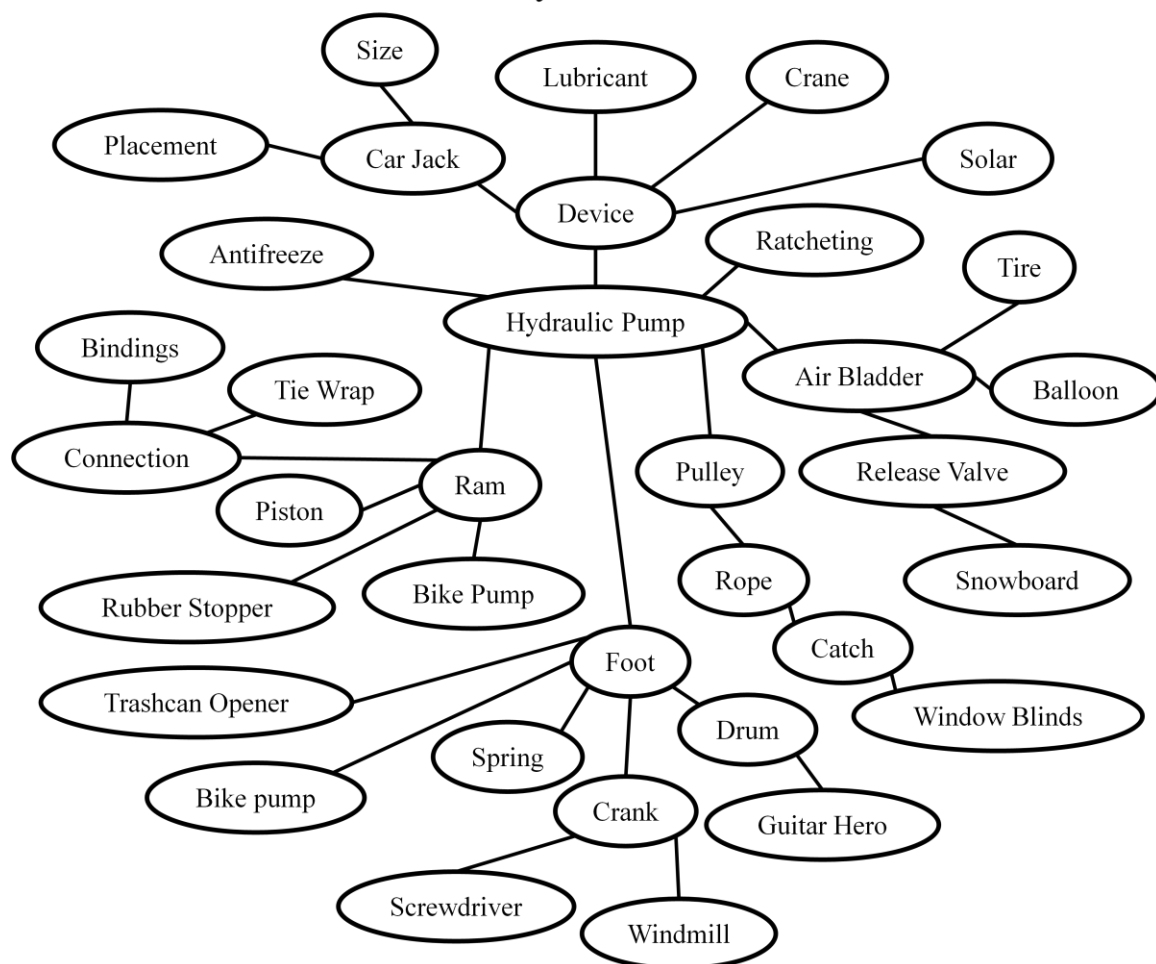
## Dyad D



Dyad E



## Dyad F





Appendix J  
Curriculum Vitae

**MATTHEW D. LAMMI****Post-doctoral Research Scholar**

National Center for Engineering and Technology Education

Utah State University, Logan, UT 84322-6000

Phone: (435) 757-1267

Email: [mdlammi@ieee.org](mailto:mdlammi@ieee.org)**EDUCATION**

Utah State University	<i>Education-Engineering &amp; Technology emphasis</i>	PhD, 2011
Utah State University	<i>Engineering and Technology Education</i>	MS, 2009
Brigham Young University	<i>Electronics Engineering Technology</i>	BS, 1999

Ph.D. Major Professor: Kurt Becker GPA: 4.0

Dissertation: Characterizing high school students' systems thinking in engineering design challenges through the Function-Behavior-Structure (FBS) framework

Masters Major Professor: Paul Schreuders GPA: 4.0

Thesis: Student achievement and affective traits in electrical engineering laboratories using traditional and computer – based instrumentation

**RECENT PUBLICATIONS****Lammi, M.** (2010). The role of problem solving in engineering and technology education. *IEEE Multidisciplinary Engineering Education Magazine*. 5, 8-13.**Lammi, M.,** Greenhalgh, S. (In Press). Having fun with a 3D projectile. *Technology and Engineering Teacher*. ITEEA.Schreuders, P., **Lammi, M.** (2010). Student attitude and achievement with computer-based instrumentation. Manuscript submitted for publishing to IJEE.**SYNERGISTIC ACTIVITIES**Denson, C., **Lammi, M.,** Park, K., Dansie, E. (2010, June). *Methods for exploring engineering design thinking in high school student teams*. ASEE Annual Conference; Louisville, KY.**Lammi, M.,** Greenhalgh, S., (2010, March). *STEM design challenge: Projectile design*. International Technology Education Association Conference; Charlotte, NC.**Lammi, M.** Mentzer, N., Park, K., Denson, C. (2010, March). *Student thinking in a STEM design challenge*. International Technology Education Association Conference; Charlotte, NC. **Lammi, M.,** Schreuders, P. (2009, March). *Methods for collecting student achievement and affective traits with virtual instrumentation*. ASEE Rocky Mountain Regional Conference 2009, Orem, UT.**Lammi, M.,** Belliston, W. (2008, November). *A compelling approach to an engineering technology service course for non-electrical engineering majors*. NAIT 2008 Annual Conference, Nashville, TN.

## COLLABORATORS & AFFILIATIONS

### Collaborators

Becker, Kurt	Utah State University
Begum, Marjahan	Loughborough University
Belliston, Ward	Utah State University
Demian, Peter	Loughborough University
Denson, Cameron	Utah State University
Greenhalgh, Scott	Utah State University
Holton, Doug	Utah State University
Hung, Woei	University of North Dakota
Mentzer, Nathan	Purdue University
Park, Kyung Suk	Utah State University
Schreuders, Paul	Utah State University

### Professional Affiliations

Institute of Electrical and Electronics Engineers	1998 – present
American Society for Engineering Education	2007 – present
Society of Hispanic Professional Engineers	2009 – present
International Technology Education Association	2008 – present

## ACADEMIC & PROFESSIONAL EXPERIENCE

Post-doctoral Research Scholar      *NCETE*, Logan, UT      12/10 – present

- Develop research in engineering design challenges
- Organize K-12 engineering design symposium
- Develop multiple research proposals
- Submitting articles to peer-reviewed journals

Teaching/Research Assistant      *Utah State University*, Logan, UT      7/07 – 12/10

- Developed and executed research in a collaborative groups studying student cognition and learning in engineering design
- Assisted with the development of proposal submissions to National Science Foundation
- Developed curriculum for electrical engineering courses
- Taught lectures and laboratories in the electrical engineering for non-majors course
- Developed and implemented innovative curriculum for electrical engineering course

Adjunct Instructor      *ITT Tech*, Sacramento, CA      8/06 – 5/07

- Instructor of record for three courses: Analog Devices, Digital Communications, and Communications Cabling
- Participated in school retention initiatives
- Instructed students in lecture and laboratory setting

- Project Manager *Avasoft*, Sacramento, CA 3/06 – 8/07
- Managed the operations of a start up business
  - Managed all research and development, including two new product varieties
  - Supervised the launch and maintenance of website and all other IT related programs
- Project Manager *Sprint-Nextel*, Reston, VA 11/04 – 3/06
- Managed 800MHz Rebanding for engineering for one half of the US (\$4+ billion)
  - Oversaw the development and launch of software programs (\$2million, \$400K)
  - Supervised team and project for legal/engineering tool saving the company over \$200M
  - Interpreted and developed documents between engineering and legal teams
- RF Engineer *T-mobile USA*, SLC, UT & NY, NY 9/00 – 10/04
- Performed overall engineering design and system performance in Utah and NY
  - Performed and analyzed drive test; used propagation modeling software and decoded footprints from drive tests aiding in system design and optimization
  - Performed various retunes and coordinated optimization and design for 2002 Olympics
  - Created and maintained training and documentation for procedures and guidelines
  - Developed and implemented software to trend system performance and indicate failures
- Communications Engineer *Lockheed Martin*, Sunnyvale, CA 8/99 – 9/00
- Conducted and directed subsystem analysis and troubleshooting for satellite program
  - Participated in initialization of new space satellite
  - Developed and implemented software program to trend subsystems' performance
  - Developed and assisted in documentation and training

#### **GRANTS AND FELLOWSHIPS**

- NCETE Doctoral Research Grant, \$10,000
- Loughborough University ESC Grant, £3,500
- Workshop Grant: International Symposium on Engineering Education, Loughborough, UK, \$3,000

#### **ACHIEVEMENTS**

- ITEEA Donald Maley Spirit of Excellence Outstanding Graduate Student 2010
- USU Graduate Student Senate Scholarship 2010 - \$4,000
- Reviewer for IEEE Multidisciplinary Engineering Education Magazine

**SKILLS**

- SPSS, R, Excel
- Microsoft Office
- Programming in Visual Basic, C, Assembly
- Fluent in Spanish