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The Engineering Design Process: Conceptions Along the Learning-to-Teach Continuum

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The Engineering Design Process:
Conceptions Along the Learning-to-Teach Continuum

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Education

by

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March 2017

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Abstract

The Engineering Design Process:

Conceptions Along the Learning-to-Teach Continuum

by

Ashley Iveland

In this study, I sought to identify differences in the views and understandings of engineering design among individuals along the learning-to-teach continuum. To do so, I conducted a comprehensive review of literature to determine the various aspects of engineering design described in the fields of professional engineering and engineering education. Additionally, I reviewed literature on the methods used in teaching engineering design at the secondary (grade 7-12) level – to describe the various models used in classrooms, even before the implementation of the *Next Generation Science Standards* (NGSS Lead States, 2013). Last, I defined four groups along the learning-to-teach continuum: prospective, preservice, and practicing teachers, as well as teacher educators.

The context of this study centered around a California public university, including an internship program where undergraduates engaged with practicing mentor teachers in science and engineering teaching at local high schools, and a teacher education program where secondary science preservice teachers and the teacher educators who taught them participated. Interviews were conducted with all participants to gain insights into their views and understandings of engineering design. Prospective and preservice teachers were interviewed multiple times throughout the year and completed concept maps of the engineering design process multiple times as well; practicing teachers and teacher educators were interviewed once.

Three levels of analyses were conducted. I identified 30 aspects of engineering discussed by participants. Through phenomenographic methods, I also constructed six conceptual categories for engineering design to organize those aspects most commonly discussed. These categories were combined to demonstrate a participant's view of engineering design (e.g., business focused, human centered, creative, etc.) as well as their complexity of understanding of engineering design overall (the more categories their ideas fit within, the more complex their understanding was thought to be).

I found that the most commonly referenced aspects of engineering design were in line with the three main dimensions described in the *Next Generation Science Standards* (NGSS Lead States, 2013). I also found that the practicing teacher participants overall conveyed the most complex and integrated understandings of engineering design, with the undergraduate, prospective teachers not far behind. One of the most important factors related to a more integrated understanding of engineering design was having formal engineering experience, especially in the form of conducting engineering research or having been a professional engineer.

Further, I found that female participants were more likely than their male counterparts to view engineering as having a human element—recognizing the need to collaborate with others throughout the process and the need to think about the potential user of the product the engineer is solving the problem for. These findings suggest that

prior experience with engineering, and not experience in the classroom or with engineering education, tends to lead to a deeper, more authentic view of engineering. Finally, I close with a discussion of the overall findings, limitations of the study, potential implications, and future work.

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Chapter 1: Introduction

In his book, *Principles of Engineering Design*, Vladimir Hubka (1982) introduced the importance of engineering design for the progress of humanity by telling a story of a shipwreck survivor. This story paints a picture of how, as humans, we have always and continue to use our environment and available resources to problem solve and meet our needs and desires. It is a familiar tale of a survivor of a shipwreck stranded on a tropical island. Problems emerge—like not being able to reach fruit on a tree—and this survivor investigates his situation, uses the resources around him, and uses his knowledge and skills to develop a solution. Hubka noted, “There are two possibilities: either he tries arbitrarily (without plan) … or, on the other hand, he may think and reflect” (p. 1). This survivor is an engineer, using the world around him to solve his problems, making plans to do so, finding quicker and easier solutions, and molding his surroundings with the forethought of solving future problems only he can foresee (you do not throw away the banana-grabbing tool after just one meal).

Engineering at its most basic is problem solving. Humans have been problem solving to make their lives better, easier, and safer for millennia. Through this process of innate engineering, humans are now at a better place, with more resources, and many more ways to solve our problems and make our lives easier. Recounting his retelling of the classic Robinson Crusoe shipwreck story, Hubka (1982) noted that through the process of engineering, “Crusoe has thereby increased his resources of technical means, and now has various additional physical effects available to him,” just as we do today (p. 2). Because this process is so basic, it is important to understand it more fully, and to ensure that the process of problem solving is not lost in future generations. To do this, I examined modern engineering design for two main purposes: to establish what engineering design is—the many smaller aspects that work together to create the large-scale process—and to inform how it can be taught.

The rationale for this study is three-fold: to add to the research in the field of engineering design, to improve the preparation of all students entering the field of engineering (or related fields), and to increase the diversity of individuals going into engineering and other STEM fields. Two of these reasons were identified by Dixon and Duffey (1990). These scholars called for more research on engineering design because of the effects that it can have on the field. They argued that research in a technical field can have two important effects: (1) It produces new people for the field. (2) It generates new knowledge. They posited that if more research were done on engineering design, it would result in design gaining more traction in the field of engineering and create important education programs on engineering design, which they viewed as critical to the success of the U.S.'s engineering and manufacturing sectors.

Many have noted that undergraduate engineering programs alone are not preparing engineers for the rigor of the field when they graduate (Blais & Adelson, 1998; Liebman, 1989; Prados, 1998; Tai, 2012). As pointed out by Brophy and colleagues (2008), in the current climate of K-12 education, the "E" in STEM tends to be de-emphasized or ignored altogether. However, there is now a push to include aspects of engineering in the K-12 science classroom with the *Next Generation Science Standards*

(NGSS Lead States, 2013). These reforms are hoping to increase the number and quality of individuals who go on to become engineers or work in the technology sector.

It is also important to increase diversity in the field of engineering, which starts with a good foundation for all students in engineering design. This is an important aspect of both the *Framework for K-12 Science Education* (NRC, 2011) and the *Next Generation Science Standards* (NGSS Lead States, 2013). Individuals from underrepresented groups have traditionally not pursued careers in engineering fields, however, this could change as students at younger ages, across all genders, ethnicities, and socio-economic statuses are exposed to engineering design in K-12 education. The *Next Generation Science Standards* (NGSS Lead States, 2013) seeks to provide *all* students access to high quality education in science *and* engineering, by incorporating engineering design standards alongside science. The hope is that more children will become interested in engineering and go on to become professional engineers one day. Not only could this benefit students going into engineering specifically, the problem-solving skills that engineering design is based on can benefit everyone, regardless of their field of study or their profession.

Overview of Study

The following questions guided this study: (1) What conceptions of engineering design did teachers along the learning-to-teach continuum hold? (2) What characteristics or experiences of participants appeared to influence their understanding of engineering design, such as their engineering experience, other STEM experiences, or personal background? I explored these two questions through qualitative analysis of 70 separate interviews and/or concept maps across 27 participants at various places along the learning-to-teach continuum. In this dissertation, I trace this study from the motivations that guided it, to implications and future research.

Chapter 2 reviews relevant research on engineering design and outlines this study's theoretical framework. In the last century, engineering design became an area with an established research base, one widely used across many fields of study, including in the professional world. I undertook a review of prior research on engineering design in an effort to identify its various aspects; through this exploration, I compiled a list of the many important aspects of engineering design. Chapter 2 also explores the various ways that engineering design is being taught, with special attention to the secondary school setting. In addition, I use the learning-to-teach continuum to contextualize the participants who are included in this study.

Chapter 3 examines the methods used in this study, including the guiding methodology and methods, contexts, data collection, and analysis. I discuss phenomenography (established first by Marton, 1981) first as a guiding theory for this study, and later, as the methods used for analysis. I also describe the study's context, participants, and data collection procedures. I interviewed participants and periodically asked a subset to complete concept maps on their understanding of engineering design. Finally, I outline the three levels of analysis used. In my level 1 analysis, I sought to uncover all aspects of engineering design discussed by participants. In my level 2 analyses, I used those aspects of engineering design to create conceptual categories by grouping related aspects together. These categories were mapped to each participant and descriptions of participants' complexity of understanding and views of engineering based on these categories were constructed. In my level 3 analyses, I looked for relationships between the conceptual categories that participants were mapped to and their experiences, contexts, and demographics.

Chapter 4 discusses the findings drawn from this study. Level 1 and 2 findings answer my first research question: What conceptions of engineering design did teachers along the learning-to-teach continuum hold? Level 1 findings describe the use and frequency of aspects of engineering design discussed by participants. Level 2 findings relate to the classification of participants into each of the conceptual categories of engineering design. Various combinations of conceptual categories are also described and participants fit into these more complex levels of combinations are identified.

Level 3 findings seek to answer my second research question: What characteristics or experiences of participants appeared to influence their understanding of engineering design, such as their engineering experience, other STEM experiences, or personal background? This level compares participants' fit into conceptual categories by their experience, context, and demographics. More specifically, I describe a subset of participants' views and understandings of engineering design over time. This was done because prospective and preservice teacher participants were interviewed and created concept maps at multiple points throughout the study year; I sought to identify any changes that may have occurred as they gained more time in either their internship or teacher education program.

Next, I discuss all participants' understanding of engineering design by their place along the learning-to-teach continuum, their prior formal and informal experiences with engineering, and their experience in the classroom -- to determine if these factors had an effect on their views and understandings. Last, I describe findings by participant demographic information. I examined whether gender, ethnicity, or academic major had any influence on which conceptual categories participants included in their descriptions of engineering design.

The final chapter discusses the overall findings of the study, potential implications and limitations, and future research directions. Main findings are reviewed and the limitations of the study—such as sample size and demographic makeup of participants—are discussed. Potential implications of this research as being broadly applied across the United States are also considered, since the *Next Generation Science Standards* (NGSS Lead States, 2013) are nation-wide standards starting to be implemented in many states across the country. I also discuss the possibilities of extending this work into the elementary school arena, to investigate elementary school teachers' views and understandings of engineering design. I argue that conducting a similar study of elementary teachers is important because this group of teachers potentially has the most to learn about science and engineering, and may have the least appropriate background and self-efficacy for teaching these subjects.

Chapter 2: Conceptual Framework

In this chapter, relevant literature will be examined that helps to answer the following questions: (1) What conceptions of engineering design did teachers along the learning-to-teach continuum hold? (2) What characteristics or experiences of participants appeared to influence their understanding of engineering design, such as their engineering experience, other STEM experiences, or personal background? More specifically, this chapter is divided into two parts. In the first section, I identify various aspects of engineering design as well as the ways it taught at the high school level. In the second section, I explain the learning to teach continuum to describe the various groups of teachers that are part of this study.

Engineering Design

Because the central question of this study centers around the concept of engineering design, it is important to examine how others in the field have defined engineering design and broken down what its various components are. In this section, I review the work that preceded, but brought about engineering design, as well as work that has been crucial to the development of what we know about engineering design today. Design itself is a broader term that relates to multiple contexts where one participates in the act of designing, including engineering, architecture, crafts, and many others. Engineering design is design specific to the field of engineering. This field is more recently established and did not come about as distinct from the more general “design” until the mid-twentieth century.

Chapter 2: Conceptual Framework

I begin with an examination of the more general field of design, which at one time encompassed engineering, before the disciplines became separate and distinct. Design is a broad term that is related to many disciplines and contexts. Archer (1968) provided pages of different definitions of design, differing descriptions of the act of designing, and multiple models of the design process in his dissertation, *The Structure of Design Processes*. Because of this varied nature, design can be studied in a multitude of ways, which Horvath (2004) explored in his own review of literature.

The first systematic studies on design came from the field of architecture in the 1920s and continued in the same vein through World War II. Harvey (1950) defined "design" as the following:

> …The design of a building (or of any other work) is the predetermined form which it is to take, existing in the mind of the architect or other creative artist; design is a work of the imagination before it can become the work of the hands. (p. 3)

He explained that people often referred to design as the graphic representation (on paper or another medium) that translated the imaginative design of the designer into a practical form (to be built). This includes blueprints, drawings, physical models, and with modern technology Harvey would not have anticipated, computer-aided design or drafting (CAD). But "these drawings…. are only the reflection of the *original* design, which is immaterial, existing in the imagination" (p. 3).

Harvey (1950) viewed design in an abstract way. However, in fields such as engineering, design took on a more concrete form, especially in industry where things are more product and profit oriented. In the post-World War II environment, the field of design was changed by the large-scale, military-type problems that were now being transferred into the private sector and civilian life, and the rapid advancement of science, technology, and engineering in government projects during the "space race" (Bayazit, 2004). Beginning in this era, the problems that engineering needed to address became more complex, and as a result, the engineering design process became more intricate (Hubka, 1982). This is the era in which research on engineering design began to take off. Literature from this pioneering era through modern work on engineering design will be examined in the following section.

The Engineering Design Process

Design is utilized in a wide range of fields and is defined in many ways. The first landmark symposium on design was held in Birmingham, UK, in 1965 and led to the publishing of a book, *The Design Method* (Gregory, 1966). In this book, it is made explicit that the process of design "is the same whether it deals with the design of a new oil refinery, the construction of a cathedral, or the writing of Dante's *Divine Comedy*" (p. 3).

As explained above, engineering design is "a specialized process of problem solving" (p. 42), where the designer first makes an effort to understand the problem, synthesizes a number of alternative solutions, the solutions are judged for how suitable they are and the best one is selected, and finally, revisions are made, which improve the chosen solution. Nigel Cross (1982), a pioneer in the field of design, viewed design as "the arts of planning, inventing, making and doing" (p. 1). While these definitions are about design in general, many see design specific to engineering as a problem-solving and/or decision-making process as well (Cross, 1982; Guindon, 1990; Hubka, 1982; Roozenburg & Cross, 1991; Wilson, 1980).

Much like science uses the methods of science to solve problems, Asimow (1962), a pioneer in the study of engineering design, argued that the engineering design process is distinctively the process for solving the problems of engineering. Gregory (1966) made a distinction between the "design method" and the "scientific method" in the types of problems to be solved by each. He claimed that both scientists and engineers are problem solvers, but the" scientific method" seeks to find out the nature of what exists, whereas the "design method" seeks to invent things of value which do not yet exist: "Science is analytic; design is constructive" (p. 6). Note that today we no longer accept the "scientific method" in the field of science education, and instead use "scientific practices" (such as those in the *Framework* and the *NGSS*; NRC, 2011; NGSS Lead States, 2013) to describe the way scientists work.

Others have also cited the distinctions between the problem solving strategies of scientists and designers or engineers (Cross, 1982; Guindon, 1990). Svensson (1974) argued that science is integral to the success of engineering design. Cross (1982) described design as "a synthesis of knowledge and skills from both the sciences and the humanities, in the pursuit of practical tasks," which is commonly associated with technology (p. 2). Like many today, Cross viewed science and engineering as complementary to one another, in that each is necessary to do the other, but the fundamental goals of each are distinct.

Chapter 2: Conceptual Framework

While groups like the Design Council propose overall models of the design process in one area, such as industry (2007), others seek to integrate the discipline-specific models of the design process to converge on one overall, universal model that can be used by engineering, architects, etc. (Roozenburg & Cross, 1991). The *Framework for K-12 Science Education* [*Framework*] (NRC, 2011) elaborated on this work on engineering design and described it as both iterative and systematic, as well as including three major steps: (1) Identifying the problem and defining specifications and constraints. (2) Generating ideas for how to solve the problem. (3) Testing potential solutions through the building and testing of physical or mathematical models and prototypes including analyzing, evaluating, and improving designs.

The *Next Generation Science Standards* [*NGSS*] (NGSS Lead States, 2013) builds on the *Framework* and seeks to provide K-12 students with a general framework with which to learn engineering design. The *NGSS* expands upon this engineering design framework as students get older, learn new information, and encounter new situations, which will enhance their abilities to solve problems in a multitude of scenarios, not just engineering.

The Three NGSS Components of Engineering Design

The engineering design process described in the *NGSS* is important to understand because it is the process that students in grades K-12 across the country will engage in. Engineering Design can be found as a separate set of Disciplinary Core Ideas [DCIs] from the traditional science disciplines (earth and space, life, and physical sciences) with corresponding Performance Expectations of students for grade bands K through two, three through five, six through eight, and nine through twelve. The process described in the *NGSS* includes three main *components* that grow increasingly complex as one progresses through the grade bands: 1) defining and delimiting engineering problems, 2) designing solutions to engineering problems, and 3) optimizing the design solution (NGSS Lead States, 2013; see Table 2a). These *components* are used as a framework for exploring the engineering design process in the following sections.

More specifically, in the next sections, the different aspects of the engineering design process, identified by experts in the field, are examined as they relate to engineering design as described in the *NGSS*. Because *NGSS* intentionally simplified its definition of engineering design and its various aspects, it is important to expand on this work to develop a more in-depth understanding of what engineering design is and of what each component consists of. Because others have noted deficiencies in the role engineering design plays in the *NGSS* (Cunningham & Carlsen, 2014), the goal in the section below is to expand on the definition and components of engineering design provided by the *NGSS* and to potentially identify aspects or essential features that are missing. I first flesh out the three components from the *NGSS* introduced above by discussing the specific aspects of each and identifying relevant literature on each. I then add additional aspects of engineering design related to the *NGSS* components, but not explicitly discussed in the *NGSS* – aspects found in the literature on engineering design. This fleshed out framework of engineering design guided my analyses.

Chapter 2: Conceptual Framework

Table 2a

Main Components of Engineering Design (NGSS Lead States, 2013, Appendix I)

Component		Description
1	*Defining and delimiting engineering problems*	… involves stating the problem to be solved as clearly as possible in terms of criteria for success, and constraints or limits.
2	*Designing solutions to engineering problems*	… begins with generating a number of different possible solutions, then evaluating potential solutions to see which ones best meet the criteria and constraints of the problem.
3	*Optimizing the design solution*	… involves a process in which solutions are systematically tested and refined and the final design is improved by trading off less important features for those that are more important.

1. Defining and delimiting engineering problems. The *NGSS* introduces this first *component* of engineering design at the earliest grades (K-2) by introducing students to "problems", which it defines as situations that people want to change, and encouraging their thinking through the needs or goals that need to be met. In grades 3-5, students are also asked to use criteria for success and constraints or limits of possible solutions when problem solving. At the middle school level (grades 6-8), this is taken one step further by asking students to take into consideration the larger context within which the problem is defined, and in high school (grades 9-12), they examine issues of social and global significance. In addition, at the high school level, problems that students engage in solving are complex and must be broken down into simpler subproblems, which can be tackled one at a time (NGSS Lead States, 2013). Below are several specific aspects of engineering design, identified in the literature, that are directly related to *NGSS* component 1: defining and delimiting engineering problems.

Problem or need. Engineering design as described in the *NGSS* begins with the problem, however, more commonly this is referred to a problem that humans identify: a *need* or *want* that they have. In addition, it is necessary to identify the "true need" to be addressed by elaborating on the initial problem or need and determining what is *truly* needed (which may differ from what was initially thought was needed). Asimow (1962), a pioneer of engineering design, discussed engineering design in *Introduction to Design*. He defined engineering design as “a purposeful activity directed toward the goal of fulfilling human *needs*, particularly those which can be met by the technological factors of our culture” (p.1).

Asimow provided a list of essential features of engineering design: 14 aspects that engineering design either is or must include. The first essential feature is *need*, which is essentially defining the engineering problem to be solved; “design must be a response to individual or social needs” (p. 5). Many others view *need* as an essential first step in the engineering design process as well. Throughout Gregory’s (1966) book, *The Design Method*, one of the main components of engineering design discussed, viewed as integral to design, is defining and researching the *need* of the customer or user. The National Academy of Engineering (2010) emphasized that engineers design solutions to problems that meet human needs or desires, and take into account identified constraints. *Need* is also the first step in the engineering method later described by Svensson (1974), Hubka (1982), and multiple others (Capobianco, Nyquist, & Tyrie, 2013; NRC, 2011; Radcliffe & Lee, 1989).

McCrory (in Gregory, 1966) stated that a major difference between the scientific method and the design method is the starting point, which begins not only with curiosity (like in science), but also with the recognition of a *need* that is social, political, or economic. This *need* is the basis on which the preceding stages of the design method must be planned and judged. Svensson (1974) viewed engineering as a bridge between scientific principles and social benefits and stated, "The objective of engineering activity is to make use of scientific principles in order to develop devices which are of value to human society" (p. 5). The first necessary feature he identified is that engineering design must be goal oriented, which means that the problem is carefully defined with clear objectives in mind. He also discussed that designers must have an ability to identify problems, because if the problem they are working through has not been carefully defined, it is their job to identify the real problem to be addressed.

Hubka (1982) also stated that the design engineer must elaborate on the assigned problem statement, to generate a more complete picture of the *true need* and the scope of the problem to be addressed. Others also discussed that the design process should begin with clearly defining the problem and the specifications of the potential solutions before proceeding on (Roozenburg & Cross, 1991). In addition, Eder (in Gregory, 1966) pointed out that it is the designer's responsibility to determine the customer's "true needs" that he or she will attempt to meet, which may be different from the original need that was stated (for example, upper management may tell a designer that the customer "needs" X, but in reality they "truly need" Y). This revelation leads to the next aspect of engineering design, in which designers must think about the potential future user(s) of their design solution.

Thinking about the user. An engineering designer must think about the person or people (the user or users) that could potentially use the solution they are designing. In a chapter of Gregory's (1966) book, Peplow expanded on thinking about customer needs and proposed methods to increase the acceptance of designs. Hubka (1982) suggested conducting research on the potential user or customer to elaborate on the identified problem or need through market research and user studies (checklists, questionnaires, case studies, etc.). In this way, Hubka suggested that engineering designers get a better idea of what their users want and how they may use the future product, which others also suggest (Dixon & Duffey, 1990; Gregory, 1966), and which is later termed *empathy* (Cross, 1982).

Research. Researching what is already out there is critical for engineering design. This includes researching existing solutions, models, or processes that can make the design process easier or obsolete all together. In addition, researching the possible tools, technology, and information related to the problem at hand can be beneficial for the engineer and the design. Many suggest conducting research on existing solutions that may aid in solving the given engineering problem, or reveal science and/or technology that can be used to solve it (Cross, 1982; Gregory, 1966; Pahl & Beitz, 1984, 2013). Guindon (1990) stated that design includes “the process of discovering missing information, such as problem goals and evaluation criteria, and using it to define a problem space” (p. 308).

In 1984, Pahl and Beitz cited the need for a systematic approach to engineering design, and proposed a product-oriented method of the design process. Their method (elaborated on in Pahl & Beitz, 2013) consists of a series of broad phases that contain smaller steps. A designer must begin the process with *product planning* and a clarification of the task, including conducting research on possible solutions that are already established to see if those could work to solve this particular problem. Ennis and Gyeszly (1991) distinguished two types of research that occurred as designers moved through the process of engineering: methodical search vs. opportunistic behavior. The methodical search for information usually occurred at the beginning of the design process before an initial concept is formulated. After an initial concept was formulated, however, opportunistic behavior was observed, where designers generated concepts while concurrently seeking information.

Identifying constraints. Identifying and developing the criteria or constraints for the engineering problem is a major component of the engineering design process and is a prominent feature in the first component of the *NGSS*. These are things that the engineer must keep in mind throughout the design process and that must be taken into consideration in the design. Constraints cover a multitude of things, including business considerations, economic factors, human considerations, technology, and many more.

Radcliffe and Lee (1989) drew from design literature to develop seven processes or stages in the preliminary design phase. The first two processes are *specification* (identifying essential and desirable requirements of the client—their needs and wants) and *main task* (formulate the inputs, outputs, and constraints on the main task—the overall goal). This second process, specification, involves identifying the relevant constraints for the engineering problem. According to the method developed by Pahl and Beitz (1984, 2013), a designer must begin the process with *product planning* and a clarification of the task, including fully developing the requirements and constraints of the project. Some of the essential features from Asimow (1962) exemplify delimiting the problem, but expand on the *NGSS's* idea of this by going beyond "constraints" in general, and includes more concrete things to look for and be aware of.

Design criterion (Asimow, 1962)—which is also included in a later component of engineering design—includes the set of standards placed on the design from the designer, producer, distributor, and consumer. Essentially the *design criterion* is the constraint that engineering designers must keep in mind throughout the process and which the solution they create must meet. Eder, a prominent voice in design research, added the element of "working constraints" to the design method (Gregory, 1966). These are things that the engineering designer must keep in mind throughout the process. Many others recognize constraints as an essential consideration of design and an important aspect of the engineering design process (Capobianco, Nyquist, & Tyrie, 2013; Cross, 1982; Dixon & Duffey, 1990; Hubka, 1982; NRC, 2011; Pahl & Beitz, 1984, 2013; Roozenburg & Cross, 1991; Wilson, 1980).

Some constraints are more common in professional engineering settings, where the design process must be more aware of business (including economic) factors. Business constraints are those that are more important from an economic perspective: Is it worthwhile for the business to have an engineer work on solving the problem? These are the kinds of questions that are important to ask when engineering design is done in a business setting, although these kinds of things are still important to understand outside of this setting. Learning about cost and availability of resources is an important skill that should be developed to help with general problem-solving skills, especially those applied to engineering.

Chapter 2: Conceptual Framework

Essential features of engineering design (Asimow, 1962) that are specific to constraints include *physical realizability* (it must be physically possible to create), *economic worthwhileness* (it must be worth more to the consumer than it costs to produce), and *financial feasibility* (there must be appropriate resources to support designing, producing, and distributing it). Other constraints include theory, manufacturing technology, economics, aesthetics, production, space, time, and consumer demands (Gregory, 1966). Many of these constraints are more aligned with professional engineering, which must take into consideration the financial viability of their potential products. While many of the features of engineering design discussed above are specific to engineering in the field, ideas such as realizability, worthwhileness, and available resources are important for K-12 students to keep in mind while going through this process.

There are many different types of constraints that must be taken into consideration depending on the specific context that an engineering designer is working within. There are considerations of human use, including safety and comfort, that some engineering designers discussed (Archer, 1968; Dixon & Duffey, 1990; Gregory, 1966; Hubka, 1982), which led to the development of *ergonomics*. Svensson (1974) stated that engineering design is "constrained" and listed the following limits on design that must be taken into consideration—many of which are also discussed by others (Gregory, 1966; Archer, 1968; Dixon & Duffey, 1990; Hubka, 1982; Pahl & Beitz, 1984, 2013; Radcliffe & Lee, 1989; Roozenburg & Cross, 1991): natural laws of physics, chemistry, mathematics, etc.; economics; human considerations; legal factors; and production facilities. Archer (1968) also discussed limitations placed on design by the government and other agencies in the form of laws, regulations, and standards, and about the financial limits of design, production, and marketing that must be considered in the form of an *investment analysis*.

The scope of design. It is important for engineers to limit the scope of the problem that they are working on for efficiency's sake. This includes realizing that if a solution to the problem at hand falls too far outside this scope that it may not be an ideal solution. Not only does this apply to what the engineers do themselves, but is also important when thinking about large scale engineering projects that must be completed by teams of engineers. In this case, an engineer must understand her or his particular scope in the larger project, and take into account what he or she should and should not be doing in the design process in relation to that scope.

Thinking of engineering design from a business perspective is even more apparent in Asimow's (1962) "methodology of design." In this process, the designer is mostly concerned with the preliminary design phases (phases one through three in his seven-phase process). Later phases primarily involve other members of the team, such as upper management, or production and distribution personnel, although designers must consider these phases as well. Archer (1968) also discussed the reality that a majority of design tasks carried out by designers are on behalf of employers or clients, rather than on their own behalf and that the standards of performance for the design is developed at the "discretion of the employer or client rather than, or in addition to, the discretion of the designer" (p. 41).

The idea of limiting the scope of the problem to be addressed by the engineer is also an essential feature of engineering design discussed by Asimow (1962): *Minimum commitment* means that only solutions that directly affect the design problem at hand should be addressed, because others are outside the scope of the project. Ennis and Gyeszly (1991) also discussed limiting the scope of design and keeping it within a “proper frame of reference” or creating “system boundaries” (p. 18). The *conceptual design* phase developed by Pahl and Beitz (1984, 2013) is part of their method of engineering design, which is only undertaken if there are no known solutions to the problem. The conceptual design phase begins with abstracting the task (describing it in the broadest way) to identify the essential problem. One must then establish the functional structures of the problem (like boundaries of the design and scientific principles) by breaking the overall problem into sub-functions that are clear. This breaking down of the larger problem is a major component of engineering design discussed in the *NGSS* (NGSS Lead States, 2013) and by many others in the section below.

Subproblems. As engineering problems become more complex, it is necessary for engineers to break these larger problems, processes, or designs into smaller subparts. In this way, they can work on one subpart at a time and bring them all together to solve the larger problem. This concept is addressed in Asimow’s (1962) list of essential features, which demonstrates how design problems can be broken down and solved one at a time. The ability to simplify problems and break them down into subproblems is an essential characteristic of a designer identified by Svensson (1974) and Archer (1968). Fricke

(1996) proposed a model of the engineering design process based on how a designer can break complex problems and overarching goals down into smaller sub-goals and targeting actions. While these systematic methods for problem decomposition at the beginning of the design process help engineers to see the intricate interconnections of aspects of the problem, Guindon (1990) suggested that opportunistic decomposition throughout the entire process may be better suited to complex, ill-structured problems which are common in engineering.

Alexander (1964) and Archer (1968) proposed the use of logical structures to represent design problems, such as interaction matrices and other diagrams, which break the larger problem down into smaller subproblems. Alexander (1964) argued that every design problem begins with trying to find a fit between the proposed solution to the problem (the "form") and the context that defines the problem; the goal is to put the context and the form into harmony with "effortless contact or frictionless coexistence" (p. 19). To do this, he suggested using a series of diagrams to sort out small, solvable design subproblems that interact with one another, determine which interactions are misfits and need to be resolved, re-evaluate that solving those subproblems did not create further misfits, and then ideally, establish that the larger design problem is in harmony (there are no more misfits among smaller subproblems).

The breaking down of larger problems into smaller subproblems has also been cited by others as a major component of engineering design as well (Hubka, 1982; Pahl & Beitz, 1984, 2013; Roozenburg & Cross, 1991) This method of problem solving exemplifies the *NGSS's* idea of breaking down large engineering problems into smaller subproblems that can be solved one at a time, but it also provides more guidance on how this is accomplished.

2. Designing solutions to engineering problems. This second component of the engineering design process encompasses the primary design activities that engineers engage in. The *NGSS* asks students in the youngest grades (K-2) to develop solutions by conveying potential solutions through visual or physical representations, which may or may not be original ideas, and to determine which solution best meets the needs and goals of the problem. In grades 3-5, students engage in research on multiple possible solutions, and at grades 6-8, students identify and combine elements of different solutions and compare multiple solutions systematically. At the high school level, students are also expected to use quantitative methods to compare different solutions using mathematics and/or computer simulations (NGSS Lead States, 2013). Below are several smaller aspects of engineering design, identified in the literature, that are directly related to NGSS component 2: designing solutions to engineering problems.

Communication. Designs that attempt to solve an engineering problem must be communicated to others. An “essential feature” of engineering design, identified by Asimow (1962), is *communication*. This describes how designs are descriptions of a possible engineering solution that are communicated through various modes (verbally, drawings or diagrams, or physical objects or prototypes). Communication of the design was also cited by Hubka (1982) as being necessary for engineering design that happens with larger, multi-member teams. Archer (1968) discussed the importance of communicating the design description as part of the design process and suggested the use of systematic models and mathematical, graphical, or physical analogues (design drawings) of the design. He posited that if a designer integrates systematic models and analogues (design drawings), they could create an operational model of the real-world problem, which can be used to test and predict the functionality of the overall design in real world circumstances.

The later phases of Pahl and Beitz's systematic method of engineering design (1984, 2013) are described as they relate to the communication of design at multiple phases throughout the process. *Embodiment design* is where the engineering designers flesh out their solution and develop a definitive layout to double-check that all of the requirements are met. From there, *a detailed design* (which includes all components, materials, forms, and finishes) is created and finally documented. The *documentation* process includes the production of final design drawings of the fully realized solution that has the potential to become a manufactured product. Their idea of using a systematic approach to engineering design is that the designer will have at least had the opportunity to make sure all aspects of the design have been thoroughly explored and lessen the likelihood that issues may arise. Drawing from Pahl and Beitz's work, Radcliffe and Lee (1989) saw multiple steps in the preliminary design phase as involving communication and documentation as well. In their processes they described how students must use sketches of their concept(s), evaluate and compare the value of those, and then, through *enrichment*, develop and create a detailed design of a chosen concept.

Gregory (1966) also discussed the need to communicate a design to others by creating a model of the design(s), which can take on many forms and varies by the stage of the engineering design process, by the particular field, as well as by the specific problem or need to be addressed. In this book, it was one of the first times that utilizing computers to aid in the engineering design process was discussed, using them to solve complex, time-consuming mathematical equations and simulations, or creating computer models of the design (commonly known as CAD today).

Later, Wilson (1980) examined in more depth how computers can aid in design as more "powerful new computer technologies" had become available, which he thought could create "a second industrial revolution" (p. 13). In addition to CAD, Wilson also discussed using Computer Aided Manufacturing (CAM) to determine how the design would go through manufacturing processes, which can aid engineers in comparing and evaluating multiple designs. Many others note that one of the major parts (perhaps the most significant) of engineering design is communicating the design in one or more ways (Capobianco, Nyquist, & Tyrie, 2013; Dixon & Duffey, 1990; Fricke, 1996; NRC 2011).

Developing solutions. A major component of the engineering design process is the development of solutions that attempt to solve the engineering problem. Developing multiple potential solutions to an engineering problem is considered to be a key part of the engineering design process (Capobianco, Nyquist, & Tyrie, 2013; NRC, 2011). It is thought to be best if an engineer develops multiple possible solutions, since not all of them will work or fit within the constraints. If there are multiple possibilities, engineers can choose which one is the best.

Svensson (1974) argued that engineering design must be *variform* because he thought that there was no limit to the number of possible solutions that one could come up with; he thought that the job of the engineer is to pick the one that is the best fit to put into practice. Radcliffe and Lee (1989) discussed techniques, such as brainstorming, that can be used to generate multiple design solution. Pahl and Beitz (1984, 2013) discussed how the engineering designer should search for and generate multiple possible solutions, then break these down into concept variants (smaller pieces of the design). Likewise, Archer (1968) discussed:

> In a particular design problem it may be possible to produce several feasible and acceptable designs. Although it is quite possible for two different designs to exhibit an identical performance, it is more usual for alternative designs to fulfill the given objectives in differing degrees. (p. 25)

Research. Researching what is already out there is critical for engineering design not only at the beginning of the process, but also throughout it. Thus, research is included both as part of the first component of engineering design as well as the second component. This includes researching existing solutions, models, or processes that can make the design better or the process more efficient. If one knows what is already out there, one can decide to abandon the project (if there is already an adequate solution), integrate aspects of prior solutions into a new one, or decide to create something completely novel. In addition, researching the possible tools, technology, and information related to the problem at hand can be beneficial for the engineer and the design. In particular, it is thought that knowing and using the most advanced resources (science, technology, methods, etc.) creates the best possible design solutions.

A feature of engineering design that is discussed throughout Gregory's book, *The Design Method* (1966), and in Archer's (1968) dissertation, *The Structure of Design Processes*, is utilizing up to date science and technology throughout the design process. By using the latest resources available, engineers can create the most innovative designs to solve engineering problems and the need of the consumer or user. Cross (1982) and others (Ennis & Gyeszly, 1991; Gregory, 1966; Guindon, 1990; Pahl & Beitz, 1984, 2013) also discussed how designers can examine and research existing objects or solutions to learn from them and apply this knowledge to help solve the engineering (or other) problem at hand. Cross (1982) argued that "objects are a form of knowledge about how to satisfy certain requirements [and] about how to perform certain tasks" (p. 225).

The concept of integrating and utilizing research throughout the design process is related to how the *NGSS* asks students to conduct research on possible solutions, and move forward with the best, most innovative one that is identified. To do this, students should use the best available methods (via science and/or technology) to evaluate their designs. Others have also stated using "state of the art" science and technology as being essential in engineering design as well (Dixon & Duffey, 1990; Hubka, 1982; Wilson, 1980). It is important to utilize the best resources available because this is thought to help improve the designs that an engineer develops and can aid in the creation of a better, more state-of-the-art solution.

3. Optimizing the design solution. The final part of the engineering design process involves taking the chosen solution and optimizing it. While students in grades K-2 are comparing, testing, and evaluating solutions (discussed in the previous section), optimization is not really introduced until grades 3-5, where students revise designs several times to obtain the best possible solution. In the upper grades (6-8 and 9-12), more systematic methods for testing and comparing designs are implemented in an effort to iteratively revise and arrive at a single optimal design to solve more complex problems. Below are several aspects of engineering design, identified in the literature, that are directly related to NGSS component 3: optimizing the design solution (NGSS Lead States, 2013).

Comparing solutions. After designs have been developed as potential solutions to the engineering problem, it is necessary that they be compared and evaluated. As part of comparing the solutions, one must look not only at them overall, but also look at how they meet the identified needs and constraints as well as the potential value (economic and otherwise) of each. Pahl and Beitz (1984, 2013) argued that engineering designers should evaluate multiple designs against some predefined evaluation criteria to determine which is best. All of the solutions are evaluated in the case that the chosen one does not solve the given problem; one or two back-up designs are then ready to be put in place.

Svensson (1974) stated that engineering design must be *value comparative* and *compromising*. The former takes into consideration the relative value (usually monetary) of each of the potential solutions, and the designer should pick one that has a high value as long as it still meets all of the other criteria. The latter requires the designer to put the satisfaction of the identified need above all else when taking into consideration multiple designs and constraints of the problem; if a design does not address the need, then it is not really a solution.

The process of evaluating multiple proposed design solutions – whether they solve the problem or meet the need, and fall within the established constraints – is commonly identified as an important aspect of engineering design (Capobianco, Nyquist, & Tyrie, 2013; Hubka, 1982; NRC, 2011; Radcliffe & Lee, 1989; Roozenburg & Cross, 1991; Wilson, 1980). This is important because if solutions have not been evaluated by this stage in the process, the following processes may hit major roadblocks and will be very inefficient if the solution that is further developed and optimized is not ideal.

Secondary effects. While most of the constraints discussed above deal with factors relating to the current engineering problem, context, and features of the design process itself (such as production and marketing), some researchers note that engineering designers should also keep in mind what happens after the product is produced and put into use. This is usually considered during the engineering design process as potential solutions are being compared and evaluated, when it can be determined what the secondary effects of each may be. Hubka (1982) discussed the secondary inputs and outputs of technical processes, especially the influences and effects on the environment that creating and using engineering solutions may have.

Asimow's (1962) final stage of a design project (Figure 4) is "planning for retirement," which he explained is what the engineering designer needed to keep in mind even at the beginning phases of the design process. He discussed how even the best solutions to engineering problems become obsolete in time, and the eventual retirement of design products must be taken into account long before they are disposed of by the designer.

If a device is made of a material that causes harm to the environment if it is placed in a traditional landfill, for example, then this product should probably not be made for an average household consumer, which would dispose of it in this way; it is not an ideal solution to the engineering problem. The “downstream” effects of design are emphasized as an important consideration in engineering design, which includes the effects on shipping, distribution, service, repair, and disposal of the product (Dixon & Duffey, 1990; Roozenburg & Cross, 1991).

Design process. Once a design has been chosen, it is the engineers’ job to move it from an abstract form (a basic idea, description, or drawing) and develop it into a more concrete form (a physical prototype or finished product). In addition, the design process must be iterative, where the engineers make systematic changes to their design and test and redesign as necessary. In Asimow’s (1962) list of Essential Features of Engineering Design, *morphology* and *design process* describe the design process going from an idea to a final design. These both describe the nature of the design process, which is both vertical and horizontal, involving iterative problem solving and a progression from abstract to concrete. These processes help optimize a solution by facilitating systematic testing and redesigning of the design.

Hubka (1982) also recognized that during design, engineers progress methodically “from the abstract towards the concrete.” which he called *conretisation*, and laid out a classification system based on his “Levels of Abstraction” (p. 22). Related to the idea of morphology is Archer’s (1968) description of the design process. His process required the designer to create initial design sketches—which can be manipulated and changed as more information becomes available—then move onto a detailed design—which is more finalized—then onto prototype construction—which is used to test the design to make sure all specifications are met—and lastly onto production design—which is a more complete, hopefully final, version of the design that includes specifications for production before the actual product is created. This design process going from the abstract to the more concrete and detailed is common among many engineering design models (Dixon & Duffey, 1990; Roozenburg & Cross, 1991).

Hubka (1982) expanded on this by laying out a series of ten steps, discussing the design documentation necessary for an engineering project. The process goes from abstract to concrete and provides more detail as one moves further along in the engineering design project. Cross (1982) also viewed the process of design as going from abstract requirements to concrete objects, but thought that the designer could go from concrete to abstract as well. He posited that one could move in the opposite direction (concrete to abstract) by examining existing, concrete objects and extracting abstract principles which could be applied in different scenarios. This is similar to the idea of researching other possible solutions and state of the art science and technology (discussed above) to apply to the specific engineering problem and context set before the designer. Guindon (1990) noticed in his study that designers would often go back and forth between more abstract and more concrete design as they revised and worked through the design process in an iterative fashion.

Asimow (1962) expanded on his feature *design process*, stating that “the design process… has an iterative character, for often, in the doing, new information becomes available or new insights are gained which require the repetition of earlier operations" (p. 44). Asimow's "methodology of design" describes the pattern all design projects go through and includes a series of major phases from start to finish. While his proposed methodology of design follows a linear flow, Asimow stated that "the design process… has an iterative character, for often, in the doing, new information becomes available or new insights are gained which require the repetition of earlier operations" (p. 44).

Archer (1968) also discussed the recursive process of design in his dissertation, *The Structure of Design Processes*. He described in detail multiple methods for solving design problems, but emphasized that the process will need to be repeated from the beginning "until the overall problem is resolved" (p. 39), with each iteration solving more and more subproblems. The shape of Archer's model of the design process takes on a horizontal spiral structure (the reiterative problem solving routine) as one gets closer to solving the design problem and further along in the overall process. Later works on engineering design also cite the iterative nature of the design process (Dixon & Duffey, 1990; Fricke, 1996; Guindon, 1990; Hubka, 1982; NRC, 2011; Radcliffe & Lee, 1989; Roozenburg & Cross, 1991; Wilson, 1980). While the iterative nature of engineering design is discussed in the *NGSS*, the notion of going from abstract to concrete is not explicitly discussed. This idea is present as they ask students to systematically optimize and redesign solutions to move from their preliminary design (discussed in the previous section) to a more finalized, optimal design solution.

Testing and evaluating. Once a design has been chosen, the engineer must determine how well that solution will actually work. First, it must be determined if it is worthwhile (economically or otherwise) to begin the process of testing and evaluating the design solution to ensure that is meets the identified needs and constraints (specifications). If it is, then systematic testing must take place where the design is evaluated based on its ability to meet the specifications. Based on how well the design does throughout testing, engineers can have confidence in their decision on the success or failure of that solution. The feedback from these tests also allows engineers to redesign and improve their design to better solve the problem.

Asimow's (1962) essential feature of engineering design, *reduction of uncertainty,* requires that engineers gather and process information on their design in an effort to gain confidence in either its success or failure to solve the problem. If there is confidence of success, the project will continue; otherwise it will be terminated, which is the *bases for decisions*. To reduce the uncertainty of the success or failure of the design, tests must be undertaken to obtain this information, and the relative costs of those test and information processing must be evaluated as well; this is *economic worth of evidence*. Dixon and Duffey (1990) discussed that while iteration and redesign can occur throughout the entire engineering design process, it is preferable to have these changes occur at the beginning of the design process because this is where changes are the least expensive to make.

Svensson (1974) also recognized that engineering design is *evaluative* and *probabilistic*, which is related to what Asimow identified above, because he saw that as new information becomes available to the engineering designer, changes and improvements may be necessary (*evaluative*), and that regardless of the information gathered and processed by them, there is always an element of uncertainty about the ultimate success or failure of a design (*probabilistic*). It is up to the designer to make sure that, despite uncertainties, the finished product will achieve the required objectives. He emphasized, though, that perfection is not the ultimate goal, only making appropriate changes to meet the need. He also thought that engineering designers should be decisive, since this is a critical characteristic necessary for good design.

Cross (1982) discussed how it is the designer's task to produce "the solution" to a problem, but that there can never be a guarantee that completely "correct" solutions can be found or are even possible; there is always an element of uncertainty and it is the engineers' job to do the best they can to find the best possible solution despite this (p. 224). The importance of testing potential solutions in an effort to improve design is seen as a key part of the engineering design process (Guindon, 1990; Capobianco, Nyquist, & Tyrie, 2013; NRC, 2011; Roozenburg & Cross, 1991).

In Gregory's (1966) book, *The Design Method*, the importance of determining the feasibility of the design is also discussed, which must be done by conducting tests of the design to see if it continues to meet the identified need and fit within the working constraints. Similarly, Wilson (1980) proposed a method for arriving at an optimal design, in which the engineer creates a design, evaluates the effectiveness of the design—calculated using Wilson's complexity metric—and then recalculates as he or she adds each constraint into the model. Hubka (1982) warned against using methods for evaluation that combine multiple measures into a single value like this, because he argued that this tends to obscure interactions of aspects of the design, may overlook long-term effects and needs, and creates an overall simplistic view of the design.

Optimal design. Once engineers have gone about the process of testing and evaluating their design, they must use the information obtained to come to an optimal design solution. This design will be the best possible version of their chosen solution and should meet the identified needs and constraints as best as possible. Some essential features of engineering design discussed by Asimow (1962) include the process of optimizing design solutions, including *optimality* and *design criterion*. *Optimality* includes choosing a design concept that is the most optimal among all the alternatives, and *design criterion* is the standards by which that design must meet including those set forth by the engineer, consumer, producer, and distributor.

Archer (1968) and Hubka (1982) call the criteria against which performance is measured the *performance* or *design specification*. Archer (1968) also stated that one must choose the optimal proposal, or the *optimum solution,* based on its ability to meet those performance specifications. Others draw on these ideas in their frameworks for engineering design as well (Gregory, 1966; Roozenburg & Cross, 1991; Wilson, 1980). Hubka (1982) also cited the need to "prepare and critically assess all necessary data," "inspect results and compare with desired value" (quality control), and eventually "choose the optimum solution for the given conditions" in engineering design (p. 29).

Archer (1968) recognized that some objectives that a design must fulfill are more important than others - higher and lower ranking objectives - and discussed how it is the designer's job to weigh these and ensure that the necessary objectives are being met with an optimal design, sometimes at the expense of other objectives not being met or not being completely fulfilled. Regardless, the goal of developing an optimal design is to come up with the best possible solution to the engineering problem that meets as many (if not all) of the identified needs and constraints as possible.

This third and final component—optimizing the design solution—is viewed as the end of the engineering design process as described in the *NGSS* (NGSS Lead States, 2013). However, it is not clear what the resulting finished product should be: a working prototype, a finished product, or a process that continues indefinitely. These ideas are discussed further in the following sections where I examine those aspects of engineering design that are absent or underdeveloped in the *NGSS*.

Added Aspects of Engineering Design

The *NGSS* created a simplified breakdown of the overall engineering design process, which is not specific to any particular field or discipline (NGSS Lead States, 2013). This is important because it was intended for students in K-12 classrooms to learn the general principles of engineering design and engage in the basic process. In their simplification, some critical aspects were either not explicit or were not included at all. In the following sections, I detail additional aspects of engineering design that were identified in the literature and that should be included in a comprehensive description of the engineering design process. I attempt to map these additional aspects to the overall engineering design process described in the *NGSS*.

Competition. Across the education continuum, competition is a method commonly used to help individuals engage in the engineering design process (discussed further below). Competition can be used to motivate designers to develop better solutions to engineering problems than their competitors. This is an additional aspect of the first component of engineering design as described in the *NGSS*: defining and delimiting engineering problems (NGSS Lead States, 2013). The sense of urgency and awareness of what others are or may be doing to solve the same or similar engineering problem is a critical part of understanding the scope of the engineering problem and what it will take to solve it (the constraints). If engineers are aware that their direct competition (whether it be a rival business or a classmate) is solving the same problem, a constraint placed on them will then be 'to create a better solution than them.' This helps drive progress and has the potential to lead to the development of better, more innovative engineering solutions.

Archer (1968) discussed how competition in the marketplace affects design decisions that are made. This is because the market will respond (usually through purchasing the product) to the product that solves the problem or need the best. Designers (especially in industry) are usually not the only ones working to solve an identified problem or need, and thus, they are competing with others to come up with the best solution and to do so in a timely manner. This is related to one of the characteristics of an engineering designer that Dixon and Duffey (1990) discussed: how more engineering design should be utilized in manufacturing to keep the U.S. competitive in the field. They argued that by designing products that are cheaper, more efficient to manufacture, and have a faster time-to-market, we can regain world leadership in manufacturing goods. Svensson (1974) identified that a sense of urgency was an important characteristic of engineers. If the process of solving the problem takes too long, either a competitor will have already solved it (making one's own solution irrelevant) or the need will no longer exist (the potential customer has moved on).

Prior knowledge and experience. The *NGSS* (NGSS Lead States, 2013) recommends students conduct research on the identified engineering problem or need and investigate potential solutions that already exist. However, it does not explicitly ask that students draw on *their own* prior knowledge and experiences with this or a similar problem in an effort to come up with solutions in the second component—designing solutions to engineering problems. While this may be implied, especially in the younger grades, it is an important skill that engineers and designers must have to be able to reflect on their own and/or others' knowledge and experiences and use that in generating designs and solutions for an engineering problem. Doing this provides greater context to engineers, helps them to make more grounded decisions related to potential solutions, and helps them develop appropriate solutions in an efficient manner.

Hubka (1982) opened his book, *Principles of Engineering Design*, with "a Robinson Crusoe story," which described a shipwreck survivor and his process of using engineering design to reach bananas on a tree. This was discussed in Chapter 1 of this dissertation. A major step in his process was to "examine whether he or someone else may have been in a similar situation, and by which means and methods they reached their target. He tries thereby to utilize existing knowledge and experience" (p. 1). Ennis and Gyeszly (1991) investigated the design process of practicing packaging engineers and found that they often drew from history (their prior experiences) when coming up with packaging ideas for given scenarios. Further, Radcliffe and Lee (1989) recognized that the undergraduate students they researched were “clearly constrained by their knowledge and experience,” which limited their generation of potential solutions to the given engineering problem (p. 206). To remedy the potential limits of only using one’s own knowledge and experience, they suggested making use of available technical information, and collaborating with others, including colleagues and experts (discussed further below).

Creativity. Design, in general, is a creative endeavor, and therefore, engineering design must also be creative. Because the goal of engineering design is to develop innovative solutions that solve a problem or need, an element of creativity must remain in the engineering design process to allow the designer to develop those solutions. This may result in a process that is less rigid and systematic since the creative designer needs more leeway to explore creative opportunities and ideas. While the *NGSS* cites that *innovation* and *creativity* are important opportunities that implementing engineering at the K-12 level might bring about, it also states that “while creativity in solving problems is valued, [the] emphasis is on identifying the best solution to a problem” (NGSS Lead States, 2013, Appendix I). Creativity is important throughout the engineering design process, but particularly in the second component of the *NGSS*—designing solutions to engineering problems—commonly called the design phase.

In his seminal book, *Notes on the Synthesis of Form*, Alexander (1964) described the process of design as a purely intuitive process of “inventing physical things which display new physical order, organization, [and] form, in response to function” (p. 1). Guindon (1990) noted that because most design involves the creation of a new technology, it requires novel ways of thinking, formulating the problem, and novel solutions to the problem. While Gregory (1966) and his colleagues attempted to describe a systematic design method, it is noted that to achieve *great* design, an element of creativity must remain.

Not only will a creative approach to design and engineering help to come up with innovative solutions, it will also help to satisfy the consumer or user, which is widely seen as the end goal of all design. In Chapter 14 of *The Design Method* (Gregory, 1966), Geoffrey Broadbent discussed the role of creativity in design in more detail and provided suggestions for enhancing creativity, including checklists, interactions techniques, and group activity. Svensson (1974) discussed that to come up with as many design solutions as possible—which he saw as a necessary feature of engineering design—designers must be imaginative, inventive, and open minded; in other words, they must be creative. Others found creativity and creative thinking as essential to engineering design as well (Capobianco, Nyquist, & Tyrie, 2013; Cross, 1982; Daly, Mosyjowski, & Seifert, 2014; Hubka, 1982).

While some scholars have sought to find systematic methods for designing, like Alexander's (1964) use of diagrams and other heuristics to solve subproblems, and ultimately the larger engineering problem, others argue that the nature of design is a creative endeavor that cannot be enacted in this manner. McCrory (in Gregory, 1966) argued that making a series of small improvements in an effort to satisfy the identified need can limit the progress of design. Rather, he thought that the designer should use "state of the art" scientific and engineering resources and creatively build on these concepts to solve problems and create new solutions. This process allows the designer to synthesize the most innovative design concepts that can be deemed feasible, put into production, and gain technical and market acceptance to become the new "state of the art" in the field.

Aesthetics. The way a designed product looks is not usually considered in most contexts where this is of little importance. Rather, other considerations take priority, like functionality and efficiency. The aesthetics of a designed solution goes beyond simply thinking about the way it looks. Rather, aesthetics consists of the overall experience that a user has with the product or process, which engineers must take into consideration when creating designs—the second component from the *NGSS*: designing solutions to engineering problems. There is a growing movement in STEM education that incorporates the aesthetic component of design, creating STEAM (Science, Technology, Engineering, Art, and Mathematics; Kim, Chung, Woo, & Lee, 2012; Yakman, 2010). While this movement in engineering education is relatively recent, aesthetics has been considered in professional engineering for decades.

In Archer's (1968) dissertation, *The Structure of Design Processes*, he dedicated an entire chapter to discussing the role that aesthetics plays in design. He clarified that aesthetics is not just whether something appeals to the eye, but to the other senses as well, and it is one of the goals of designers to make sure that their design is appealing in these ways. He noted that aesthetics in conjunction with the overall satisfaction of the consumer's needs come together to create a *whole experience* for the costumer, which, if satisfactory, promotes the sale of the product and creates economic worth of the product.

Hubka (1982) and others (Dixon & Duffey, 1990) also described appearance as an essential consideration for engineering design.

Simplicity. Engineers need to be efficient in their own design process as well as create efficient designs and solutions. To ensure the efficiency of a design, it is usually assumed that simpler is better. If a problem can be solved using a simpler design, then that usually takes less time to create and produce, reducing waste. While the *NGSS* (NGSS Lead States, 2013) asks students to compare multiple solutions (Component 2: Designing Solutions to Engineering problems) and optimize design solutions (Component 3: Optimizing the Design Solution), it does not expressly discuss that designs should be the simplest possible solution that can solve the problem.

This notion of simplicity in design is common in business and industry, where the cost of the product is directly correlated to the materials and resources used. The simpler the design is, the less it costs to make, and the lower the cost to the consumer (which is desirable). While this is something that is usually not as important or apparent in K-12 education, availability of resources (including time) is an important constraint on designing that should be taught, and thus, students should acknowledge that a simple design that solves the problem in an efficient manner is usually best.

In Wilson's (1980) *An Exploratory Study of Complexity in Axiomatic Design*, the ancient axiom "keep it simple, stupid" (p. 12) is expanded upon as a principle of design, and a method for determining a design's *simplicity* or *complexity* is developed. He drew on information theory and thermodynamics, specifically entropy, to develop measures of complexity of a design that can be used in comparing multiple designs in an effort to select one that is the simplest, while still solving the engineering problem. It is postulated that this measure of complexity is important as it explains common manufacturing phenomena in a fundamental way.

Similarly, Hubka (1982) and others (Roozenburg & Cross, 1991) argued that an engineer should reflect upon a design solution to determine if a simpler solution would meet the desired objectives with less use of resources and/or energy. In a study of undergraduate engineering students, Radcliffe and Lee (1989) gave the highest scores to students who created “simple and sound” designs, meaning that the design not only performed its “required function”, but was also the simplest possible design that could do this (p. 202).

Collaboration. An important part of effective engineering design is collaborating with others to capitalize on their expertise. This is also important because it lessens workload and provides valuable insights and feedback that one engineer may not have thought about in isolation. The *NGSS* encourages students to work together to engage in engineering design, however, they do not expressly *require* that students do this. This may be a missed opportunity, as many researchers have discussed the need to work with others while engaging in engineering design to gain multiple perspectives, areas of expertise, and to lessen the workload on any one individual. Collaboration is part of the overall design process, which we discussed in component three of the *NGSS*: optimizing the design solution.

Gregory (1966) and his colleagues discussed that communicating among all members involved in the engineering design project as well as those outside of the project was critical to the success of the design process and to the creation of an innovative solution to the problem. In his book, *Principles of Engineering Design*, Hubka (1982) recognized that most engineering projects are too complex and large to be taken on by one person alone, and therefore, engineering design requires teamwork and collaboration. He also recognized that this collaborative nature requires design activities to be clear and communicated in a manner that all team members can “see, review, criticize, evaluate, decide, and do all the activities needed to create and make a new project” (p. 3).

Capobianco, Nyquist, and Tyrie (2013) also recognized that collaboration is essential for today’s engineers, and thus, sought to incorporate it as an essential feature to teaching engineering design. An essential part of the engineering design process used by undergraduates in Radcliffe and Lee’s (1989) study was collaboration. The conversations and interactions among group members allowed for the development of ideas and concepts to solve the engineering problem. They viewed the principle of collaboration as essential to engineering design and a major component to improving design education.

Evolutionary design. It is important to note that the engineering design process undertaken in our modern technological society is much different than the intuitive problem solving process done informally, which happens over long periods of time. The intuitive problem solving process that humans naturally engage in for informal engineering design is centered around ‘trial and error’ and is usually a longer and less efficient process than formal engineering design. This kind of problem solving process is referred to as evolutionary design because small changes occur over long periods of time as the solution changes and ‘adapts’ to solve the problem. In *evolutionary design*

(Alexander, 1964; Cross, 1982; Dixon & Duffey, 1990; Gregory, 1966; Hybs & Gero, 1992), knowledge is passed on through generations, therefore the design fits the problems of the environment quite well because it has been tested repeatedly with small iterations and revisions being made as new problems arise.

Hubka (1982) explained that in evolutionary design, humans rely on *natural laws* (their prior experiences and observations), which associate cause and effect. He called this "qualitative prediction" (p. 6). Later, quantitative prediction followed and then mathematical models and procedures as technology and design became more complex. The problems to be solved in a more complex context are not suited to this kind of evolutionary design. This method usually takes more time than a more systematic method—like those described above—however, this evolutionary approach can sometimes be the best method for unconventional problems and solutions or when conventional problem solving techniques have not worked to develop a solution. The notion of evolutionary design is related to the design process described in component 3 from the *NGSS*: optimizing the design solution.

Final product. The final part of the engineering design process involves creating a final product or process that is the ideal and optimal solution to the identified engineering problem or need. The final product is usually an indication of the end to the engineering project, and the end of the engineers work on that problem. This is different from the discussion of an optimal design above, since this aspect of engineering design requires that a final product is created that can go to market and that the engineer may relinquish ownership of this final product. This is not necessarily the case with an optimal design—which may still be a design and not a final product ready for market—where the engineer may still work extensively with the design: testing, revising, developing manufacturing strategies, etc.

While the *NGSS* (NGSS Lead States, 2013) expects students to go through the process of optimizing a design solution to arrive at a single optimal design (in the last component, optimizing the design solution), they do not explicitly ask that students create a final product from that design. From this perspective, the engineering design process ends prematurely, before students can actually create the thing that they have designed in a form that is usable to the person/people they intended it to be used by. Creating a complete, final product that can be used by the proposed user(s) can demonstrate to students the *full* engineering design process and how long it can take to go from beginning to the absolute end.

Asimow's (1962) "methodology of design" and McCrory's design method (in Gregory, 1966) allude to the fact that the engineering design process creates a final product that will be produced, marketed, distributed, consumed, and retired. In other chapters of Gregory's (1966) book, the importance of creating a final product that is consistent with the final design and meets consumers' needs is explicitly discussed, and the particulars about the production and manufacturing of those final products are explored. Archer (1968) also talked extensively about how the designer goes through multiple steps in the design process in an effort to produce and sell a final product that meets all of the requirements necessary. He recognized that once the final product is created and all defects are rectified, the designer must relinquish possession of the design and product to the owner (the client). This is typically the end of the process for the designer unless feedback on the product is provided.

Never ending process. While many, including the *NGSS* (NGSS Lead States, 2013), have talked about the iterative nature of engineering design (see component 2 above), which creates one or more *loops* in the design process, some argue that true design is never complete and that true engineering design takes on the form of a closed loop. The engineering design process is sometimes viewed as being never ending because new problems are constantly arising and designs can always be improved, especially as feedback and further research is conducted. Sometimes this cycle is quite short and resembles the iterative redesign cycle discussed in the final component of the *NGSS* above (optimizing the design solution), or a larger feedback loop that is provided after the final product has been used for some time and new technology reaches the marketplace. This is a direct contrast with the above idea of engineering design, which necessitates the creation of a final product as a result of the engineering design process. While creating a final product does not necessarily mean that the process is completed, those who view engineering design as a never ending process do not tend to identify a final product as a main component of the process.

A graphical representation of the design method was given by McCrory, which shows the process as a closed loop with a series of steps and inputs with interconnections that flow to and from one another (Gregory, 1966). As stated above, McCrory discussed that in innovative, creative design, the engineer can take what is and create something new from it. If this is done successfully, their design will go into production and become the new “state of the art” in the field and/or saturate the marketplace. Once this occurs, a designer can reiterate the design method with a new need in mind, creating the closed loop: The design process is never complete and designs can always be improved to meet new needs. Similarly, Archer (1968) recognized that at the end of the design process, it is necessary to get feedback on the market and user information so that the product can be improved, and the process can be worked through again.

Like Gregory (1966) before him, Svensson (1974) conceptualized the engineering method as a closed loop with the main phases commencing in a linear manner, but with “modification” and “revision” connecting all of those phases back to either the “concepts” or “need” phase to create loops that allow the designer to iterate any part of the process as needed. The main phases are concept development (the inventive phase), validation of the design concepts and establishment of performance prediction (the analysis phase), and the selection of the most appropriate design concept (the decision phase). This more open model, which allows the designer to move freely from any phase of the process back to an earlier phase, allows for the potential for creativity and innovation as new ideas can be incorporated at any time throughout the process. The fact that the loop is closed also implies that the engineering design process is never complete as designs and products can always be improved, and new needs always emerge. In addition, this model is broad enough to be appropriately utilized in many fields, rather than just in engineering.

Table 2b

Identified Aspects of Engineering Design by NGSS Component

NGSS Component	Identified Aspect
1. Defining and delimiting engineering problems	**Problem or need** The first step in the engineering design process is to identify the engineering problem, which is usually a human "need" or "want". In addition, it is necessary to identify the "true need" to be addressed by elaborating on the initial problem or need and determining what truly needed `(which may differ from what was initially thought was needed).
	Thinking about the user An engineering designer must think about the person or people (the user(s)) that could potentially use the solution they are designing. To do this is to "empathize" with the user. This can include researching the marketplace or conducting user studies.
	Research Researching what is already out there is critical for engineering design. This includes researching existing solutions, models, or processes that can make the design process easier or obsolete all together. In addition, researching the possible tools, technology, and information related to the problem at hand can be beneficial for the engineer and the design. This is part of component one because you are researching the problem and/or constraints before engaging in any design.
	Identifying constraints Identifying and developing the criteria or constraints for the engineering problem. These are things that the engineer must keep in mind throughout the design process, and that must be taken into consideration into the design. Business constraints are those that are more important from an economic perspective—including financial feasibility, time, legal consideration, and analyses of economic factors. There are a number of other possible constraints, including (but not limited to) the natural laws (e.g. the laws of physics, etc.), human considerations and use (e.g. ergonomics), and many more.
	The scope of design It is important for engineers to limit the scope of the problem that they are working on for efficiency's sake. This includes realizing that if a solution to the problem at hand falls too far outside this scope that it may not be an ideal solution.
	Subproblems As engineering problems become more complex, it is necessary for engineers to break these larger problems, processes, or designs into smaller subparts. In this way, they can work on one subpart at a time and bring them all together to solve the larger problem.
2. Designing solutions to engineering problems	**Communication** Designs that attempt to solve an engineering problem must be communicated to others. To do this, designs can be communicated using multiple modes—verbally, visually, mathematically, through writing, or some other form. Examples of designs that are communicated include written or spoken descriptions, drawings, prototypes or models, computer aided designs (CAD), mathematical models or equations, etc.
	Developing solutions A major component of the engineering design process is the development of solutions that attempt to solve the engineering problem. It is considered best if an engineer

	develops multiple possible solutions, since not all of them will work or fit within the constraints. If there are multiple possibilities, you can choose which one is the best. **Research** Researching what is already out there is critical for engineering design not only at the beginning of the process, but also throughout it. This includes researching existing solutions, models, or processes that can make the design better or the process more efficient. In addition, researching the possible tools, technology, and information related to the problem at hand can be beneficial for the engineer and the design. In particular, it is thought that knowing and using the most advanced resources (science, technology, methods, etc.) creates the best possible design solutions.
3. Optimizing the design solution	**Comparing solutions** After designs have been developed as potential solutions to the engineering problem, it is necessary that they be compared and evaluated. As part of comparing the solutions you must not only look at them overall, but also look at how they meet the identified needs and constraints and the potential value (economic and otherwise) of each. **Secondary effects** Engineers must keep in mind what happens as a result of creating and using the design solution. This includes effects of producing the solution as well as effects of using it, and what will happen once it is retired and no longer needed. **Design process** Once a design has been chosen, it is the engineers job to move it from an abstract form (a basic idea, description, or drawing) and develop it into a more concrete form (a physical prototype or finished product). In addition, the design process must be iterative, where the engineer makes systematic changes to their design and test and redesign as necessary. These process help optimize a solution by facilitating systematic testing and redesigning of the design. **Testing and evaluating** Once a design has been chosen, the engineer must determine how well that solution will actually work. First, it must be determined if it is worthwhile (economically or otherwise) to begin the process of testing and evaluating the design solution to ensure that is meets the identified needs and constraints (specifications). If it is, then systematic testing must take place where the design is evaluated based on its ability to meet the specifications. Based on how well the design does throughout testing, an engineer can have confidence in their decision on the success or failure of that solution. The feedback from these tests also allows the engineer to redesign and improve their design to better solve the problem. **Optimal design** Once an engineering has gone about the process of testing and evaluating their design, they must use the information obtained to come to an optimal design solution. This design will be the best possible version of their chosen solution and should meet the identified needs and constraints as best as possible.
Added Aspects— *Mapped to NGSS Components*	*NGSS Component 1:* **Competition** Competition can be used to motivate designers to develop better solutions to engineering problems than their competitors. The sense of urgency and awareness of what others are or may be doing to solve the same or similar engineering problem is a critical part of understanding the scope of the engineering problem and what it will take to solve it (the constraints). If an engineer is aware that their direct competition is solving the same problem, a constraint placed on them will then be 'to create a better solution than them'. This helps drive progress and has the potential to lead to the development of better, more innovation engineering solutions.

NGSS Component 2: **Prior knowledge and experience**
Engineers should draw on their own prior knowledge and experiences of similar situations when developing solutions for a given engineering problem. Doing this provides greater context to the engineer, helps them to make more grounded decisions related to potential solutions, and helps them develop appropriate solutions in an efficient manner.

NGSS Component 2: **Creativity**
Design, in general, is a creative endeavor, and therefore, engineering design must also be creative. Because the goal of engineering design is to develop innovative solutions that solve a problem or need, an element of creativity must remain in the engineering design process to allow the designer to develop those solutions. This may result in a process that is less rigid and systematic since the creative designer needs more leeway to explore creative opportunities and ideas.

NGSS Component 2: **Aesthetics**
The aesthetics of a designed solution goes beyond simply thinking about the way it looks. Rather, aesthetics consists of the overall experience that a user has with the product or process, which engineers must keep into consideration when creating designs.

NGSS Component 2: **Simplicity**
An engineer needs to be efficient in their design process as well as create efficient designs and solutions. To ensure the efficiency of a design, it is usually assumed that simpler is better. If a problem can be solved using a simpler design, then that usually takes less time to create and produce; reducing waste.

NGSS Component 3: **Collaboration**
An important part of effective engineering design is collaborating with others to gain capitalize on their expertise. This is also important because it lessens the work load on any one individual and provides valuable insights and feedback that one engineer may not have thought about in isolation.

NGSS Component 3: **Evolutionary design**
The intuitive problem solving process that human naturally engage in for informal engineering design is centered around ‘trial and error’ and is usually a longer and less efficient process than formal engineering design. This kind of problem solving process is referred to as evolutionary design because small changes occur over long periods of time as the solution changes and ‘adapts’ to solve the problem.

NGSS Component 3: **Final product**
The final part of the engineering design process involves creating a final product or process that is the ideal and optimal solution to the identified engineering problem or need. This is no longer a design, but something that can and does go into production, which the engineering no longer has control of. The final product is usually an indication to the engineer of the end to the engineering project, which they will most likely never return to.

NGSS Component 3: **Never ending process**
The engineering design process is never ending because new problems are constantly arising and designs can always be improved, especially as feedback and further research is conducted. Sometimes this cycle is quite short and resembles the iterative redesign cycle discussed in the final component of NGSS above (Optimizing the design solution) or a larger feedback loop that is provided after the final product has been used for some time and new technology reaches and marketplace. With this view of engineering design, an engineer’s work is never done.

Chapter 2: Conceptual Framework

Framework for Engineering Design

The previous sections detailing the various components from the engineering design process in the *NGSS*, as well as all of the aspects of each have been combined into an overall framework for engineering design (Table 2b). This framework covers all parts of the engineering design process, from the initial identification of the problem or need, through to the creation of a final product that can go to market. This framework is important because it expands greatly on the description of engineering design given in the *NGSS*, which could otherwise limit the knowledge and understandings that educators and students have about the process and how to engage in it.

Additionally, it is particularly important that students at the high school level fully understand the engineering design process since many current and emerging fields (even those outside of engineering) utilize many, if not all, of the aspects described here to problem solve. If students wish to be fully prepared for college or vocation education and to become assets in the workforce, then learning about and engaging in all components and aspects of engineering design are critical.

Teaching Engineering Design

Now that the many aspects of engineering design have been established and discussed in depth, I detail the various methods used to teach it. Engineering design must be taught as a critical aspect of education, not only for engineering, but also for the sciences. Early researchers argued that design was an essential foundation of education (Archer, 1982), and Cross (1982) elaborated on the need to include design as a "third area" of education (rounding out the sciences and humanities). He argued that design was a distinct educational area that included its own language, culture, methodology, etc., which could and should be taught to all students, rather than just those who chose to specialize in the field. Included in these characteristics of engineering as a distinct area is the "language of modeling," pattern formation and synthesis, the study of "the man-made world," and a culture of "practicality, ingenuity, empathy, and a concern for appropriateness" (p. 221). Cross laid out three main areas of justification for including design in general education:

> 1) Design develops innate abilities in solving real-world, ill-defined problems.
> 2) Design sustains cognitive development in the concrete/iconic modes of cognition.
> 3) Design offers opportunities for development of a wide range of abilities in nonverbal thought and communication. (p. 226)

Research has already suggested that teaching science using authentic engineering design-based methods is superior for student learning compared to the traditional scripted inquiry approach (Mehalik, Doppelt, & Schuum, 2008). Some have even developed teaching guides for high school teachers who wish to incorporate engineering into their mathematics or science curriculum (Titcomb, 2000). Finally, engineering design has been incorporated into science instruction at the K-12 level, on a national scale, with the implementation of the *Next Generation Science Standards* (NGSS Lead States, 2013). Looking at how engineering is taught at the high school level, in particular, is important because this is one of the first educational settings where students are exposed to and engage in more complex engineering practices and design. Below, I discuss several reasons it is important to teach engineering design at the high school level.

One reason that teaching engineering design at the high school level is important is to provide a good foundational education for engineering students. Studies on the design behavior of students at the university level, conducted by Lawson and others (as cited in Cross, 1982, pp. 223-224), found that first-year students in architecture, urban design, and engineering did not hold distinct “designer” problem solving strategies, whereas students at the graduate level in these same fields did. This suggested that their engineering education had a profound effect on the way these designers conceptualized and worked through problems. In most instances, before the implementation of *NGSS*, students have had no prior experience in engineering design before college, and therefore, had no way to gain these strategies and understandings to be prepared for college.

Teaching engineering design in high school can be seen as a stepping stone for the process of educating practicing engineers because a great deal of foundational knowledge and a long list of practices can be learned and reinforced before the more formal education at the university level. Some programs create cooperation between high school and colleges or universities, which provide students with a seamless link between their engineering learning in the two educational settings. It is important having this foundational step in the engineering education process, since many have noted that undergraduate engineering programs alone are not preparing engineers for the rigor of the field when they graduate (Blais & Adelson, 1998; Tai, 2012).

Chapter 2: Conceptual Framework

Throughout the mid-twentieth century, university engineering education programs produced a generation of students who were well versed in the fundamentals of engineering "science", but deficient in the ability to "do" engineering (Liebman, 1989). Prados (1998) discussed the many weaknesses that industry cited in recent engineering graduates, such as the following:

1. No understanding of manufacturing processes
2. Lack of design capability or creativity
3. Lack of appreciation for considering alternatives
4. Lack of appreciation for variation
5. Poor perception of the overall project engineering process
6. Narrow view of engineering and related disciplines
7. Weak communication skills
8. Little skill or experience in working in teams (pp. 2-3)

Dixon and Duffey (1990) argued that these deficiencies in the field could be improved or remedied with increased education and research efforts on engineering design, and support from industry and government agencies. By introducing engineering design in high school, it will increase the amount of time that students can learn and engage in engineering before entering a more formal engineering setting.

Another reason that teaching engineering design at the high school level is important is because it allows all students—not just those who go on to do engineering—to develop skills and practices, such as design and problem solving skills, which can be applied in any field they choose to pursue after high school. This foundation of engineering through *NGSS* at the high school level is broad enough (mostly encompassing basic engineering habits of mind, practices, and engineering design) to be applicable in any area of engineering, as well as many fields outside of engineering.

Additionally, including engineering at the high school level may help students decide if a STEM career path is right for them. Not only do engineering programs and courses at the high school level help those students who want to go on to engineering programs either professionally or at the collegiate level, but it can attract a larger number and a broader range of students to the field (Kopietz, Harrington, & Lodaya, 2013; Tai, 2012). This is because they will have earlier exposure to engineering and can then make an informed decision about if it is right for them (Blaise & Adelson, 1998). Studies have shown that a majority of professional scientists and graduate students chose their career field during high school (NRC, 2008), and similar trends are found for the larger STEM area (Maltese & Tai, 2011). This indicates that the STEM experiences that students have in high school have a large impact on whether they go on to study or have a career in those fields later on.

The ways that engineering design have been taught at the high school level are explored below. While there is not much literature on engineering education specifically for high school—since this is a relatively new aspect of education at this level—the ways that it is being done, specific examples, and an attempt at understanding some of the potential best practices are discussed.

The structure of engineering education. There are various models for engineering education that have arisen throughout time, some of which are viewed as more successful than others, and some of which are more appropriate for individuals at different stages of their education than others (high school vs college). Two of the primary models used to teach high school students (and others) engineering are discussed below.

Apprenticeship. One primary means of educating engineers and other designers throughout history has been through apprenticeship (Gregory, 1966). An apprenticeship model is one where a ‘novice’ works closely with a more experienced ‘expert’ in the field and learns from them while working on projects. Novices gain more autonomy as they get more experience and understanding over time, and eventually they will themselves become ‘experts’. Cross (1982) recognized the apprenticeship model as the traditional model for design education in which students “act out the role of designer in small projects and are tutored in the process by more experienced designers” (p. 222).

While an apprenticeship model would traditionally require ‘novice’ designers to work in a particular field to learn from ‘expert’ designers, some argue that it is possible to educate all designers using this model, regardless of their specialty. This more comprehensive type of apprenticeship model would be more appropriate for the kind of engineering done at the high school level. Roozenburg and Cross (1991) developed an integrated model of engineering design that provides guidelines and suggestions, “without prescribing in detail” how to do things. Their integrated mode, “does not restrict designers to just one way of working… instead it tries to organize the problem-solving behavior of designers to such an extent that it is more effective and efficient than intuitive, unaided, unsystematic ways of working” (p. 216). Campbell and Colbeck

(1998) broke down the various approaches used to teach engineering design and determined the four most common, two of which are apprenticeship models: faculty as a guide or coach, and industry involvement. With these approaches, the novice is learning from an expert in the field about the practices and knowledge necessary to do engineering design.

Many high schools follow an apprenticeship model for their engineering courses or projects by bringing in professional engineers or teachers experienced in engineering to mentor and guide ‘novice’ high school students. At San Diego’s High Tech High, courses are structured so that they work on a single project and go through the engineering design process in an effort to solve a problem relevant to the course content (Rubenstein, 2008). Often, at the end of the course, community members, experts in the field, clients, or others evaluate their projects, or their work is shared, often through displaying it prominently at the school or other local agency. Additionally, juniors spend a full semester working at internships tailored to their needs and interests. The deep relationship that High Tech High fosters with local groups, businesses, and experts exemplifies the apprenticeship model, while still giving students enough autonomy to engage in authentic engineering design in the classroom.

Project Lead the Way, considered a leader in the apprenticeship model at the high school level, brings schools, colleges and universities, and industry together to increase the number of students graduating from engineering and technology programs and to improve the quality of those students once they enter the field (Blaise & Adelson, 1998). Project Lead the Way partners mentors from industry and colleges or universities with high school students in project-based learning activities that require teamwork and problem-solving. They are also one of very few programs that include engineering faculty as instructors (Tai, 2012). The program is roughly “one-third theory and two-thirds application” (p. 40). In addition, Project Lead the Way includes multiple courses on engineering design: Introduction to Engineering Design, Design and Rapid Prototyping, and Engineering Design and Development.

An important feature of the apprenticeship model when applied to the high school education setting is to ensure that the relationship with ‘experts’ is maintained. If these relationships (often found in partnerships with industry and colleges or universities) dissolve, then students will no longer benefit from working closely with those who have experience and expertise in the field, which could mean failure of the program. Large-scale high school engineering projects, like Project Lead the Way, assure the continued success of relationships between schools, industry, and colleges or universities by organizing multiple leadership groups that support and direct the program. These groups include: a national oversight committee, regional leadership teams, a school district advisory council, a partnership team, a school district education committee, and project action teams (Blaise & Adelson, 1998). In these leadership groups—especially the regional leadership team and school district advisory council, which is comprised of representatives from industry and colleges in addition to school and district representatives—relationships between all the players involved are reinforced.

While the apprenticeship model for engineering is viewed as ideal by many, others have expressed concerns about its use in the K-12 context. Unlike teaching design at the undergraduate or professional level, where traditional models like the master-apprentice relationship can be effective, it is noted by some that this is not ideal for K-12 education because these teachers typically do not have specialized education in engineering (Cross, 1982; Cunningham, Knight, Carlsen, & Kelly, 2007). Educators teach best when they understand the content and feel comfortable teaching it, but this is usually not the case with engineering (Cunningham, Knight, Carlsen, & Kelly, 2007). While this may prove problematic, teaching engineering at the K-12 level allows for opportunities to incorporate best teaching practices, pedagogy, and the integration of multiple subject areas with engineering design. One way of ensuring teachers are well-versed in engineering is by providing in-depth training on engineering and technology. This was found to be successful in increasing teachers' self-assessed knowledge and comfort with engineering design. Some high schools and programs do just this, provide training for their teachers on engineering content, technology, and engineering design.

For example, Project Lead the Way involves extensive teacher training that includes one teacher undergoing intensive, semester-long training at a local participating college or university (Blaise & Adelson, 1998; Tai, 2012). There, they take courses, familiarize themselves with applicable technology, and learn about engineering from a college mentor. This is a type of apprenticeship arrangement as well, where the teacher is at first the 'novice' learning from their college mentor, but by the end of their semester-long training the teacher becomes the 'expert' who can then go on to mentor their 'novice' high school students. In addition, all other teachers in the program participate in one- to two-week trainings in the summer and also review and revise their engineering curriculum regularly in teams.

Capstone projects. A second model widely used to teach engineering design involves giving students a larger project to work through at the culmination of their education program or course (a capstone project). Capstone engineering projects have been widely used in the undergraduate setting and are beginning to gain traction in K-12 classrooms as well. Banios (1991) found that there was a large movement towards using "capstone" design courses, but cautioned that these types of courses may not be ideal if done incorrectly. Dutson, Todd, Magleby, and Sorenses (1997) provided a review of literature on teaching engineering design specifically through capstone courses. They found that these types of courses were generally beneficial in teaching engineering practices, however, others argue that these kinds of project-based courses tend to focus on product over process.

Mentzer, Huffman, and Thayer (2014) discussed that projects in engineering courses tend to be mostly, if not entirely, evaluated on the final product, rather than the process that students went through to get to that product. While having this approach makes assessment easier, educators are not truly analyzing whether students understand the practices of engineering, such as modeling and engineering design, because those things are not evident when looking at the final product alone. Campbell and Colbeck (1998) also found that instructors who use design projects tend to assess students on the quality of the final product produced, rather than looking at students' design competence to assess their performance during the entire project.

Another critic of capstone engineering courses is Bordogna, Fromm, and Ernst (1995), who viewed them as “passing through the filters” of basic science and mathematics courses before students can do any actual engineering or design. In the traditional undergraduate engineering program, an engineering student would take basic science and mathematics courses for much of the program, and only do a capstone project at the conclusion of the program as a way to bring it all together. Since it has been shown that a single, overarching capstone project at the conclusion of an engineering program may not be an ideal model for engineering education (Bordogna, Fromm, & Ernst, 1995; Campbell & Colbeck, 1998; Mentzer, Huffman, & Thayer, 2014), some suggest smaller projects that are completed throughout the engineering education process.

Bordogna, Fromm, and Ernst (1995) proposed an integrative and holistic approach, where students learn the functional core of engineering “up front,” and gain in-depth science and engineering experiences through research in addition to multiple capstone engineering courses throughout their education. They argued this format will increase interest in engineering as well as help students “learn how to define problems, consider alternative solutions, and simultaneously experience the excitement and frustration caused by creative design, limited knowledge, and open-endedness in creating a new product, system, or enterprise” (p. 194). Carlson and Sullivan (1999) described the Integrated Teaching and Learning (ITL) program where engineering students at all levels could design and create engineering solutions, from kinetic sculptures, to assistive technology for the disabled or elderly. They argued that allowing students at all levels of engineering education to engage in these kinds of projects created an active learning environment that would support deep learning of the practices, process, and concepts of engineering.

A model high school (called the “engineering academy”) that utilizes capstone projects was discussed by Harlow and Hansen (2015). In this high school, students participate in an overarching capstone project their senior year, a culminating project that brings together everything they have learned throughout their four years in the program. This overarching capstone project involves working collaboratively with the whole class, in smaller groups, and with teachers, mentors, and engineering professionals to create a large installation. Students also worked on smaller aspects of this project individually, but needed to keep in mind what others were doing to ensure the overarching goals and constraints were being met.

The “engineering academy” (Harlow & Hansen, 2015) also asks students to complete smaller-scale projects each year they are in the program. These smaller projects start practically day one of the program, when students are in ninth grade, and become progressively more involved, requiring more knowledge and skills in science, mathematics, computer-aided-design (CAD), art, and machining. Because these smaller projects build on what students are learning and doing throughout the program and allow them the opportunities to apply their knowledge and skills in authentic ways, this high school’s engineering program can be a model of using capstone projects effectively.

On a smaller scale, High Tech High utilizes project learning at the individual course level, where students complete smaller projects that solve an identified problem related to the courses’ content (Rubenstein, 2008). These projects can culminate in scientific procedures (that are made more efficient) and/or products or displays for the community or school, client-driven products, or ideas or solutions to political, environmental, or social issues. These smaller scale projects can be done in isolation in a single class, or can be combined across multiple classes or subjects to create larger projects that solve bigger, interdisciplinary problems that serve a larger audience.

Methods for teaching engineering design. Beyond the structure of engineering programs, there are particular methods for teaching engineering design that can be applied in both large-scale (program-wide) or small-scale (single lesson) settings. Strategies, like modeling engineering design, integrating engineering with other disciplines or fields, and creative collaborative or competitive environments can foster engagement in engineering design if done correctly. I discuss four strategies for teaching engineering below.

Modeling the engineering design process. One method for teaching engineering design is to provide students with small-scale engineering problems and have them work through those while following a model of the engineering design process (Fricke, 1996; Gregory, 1966). The *NGSS* provides students with a basic, three-step model of the engineering design process that they can use as a framework to guide their working through an engineering problem. This basic framework is helpful because it provides some structure and guidance to what could otherwise be a chaotic, messy process, but also because it is not so detailed that it limits the possibilities of students to choose their own path and explore other avenues and methods for solving the problem.

Chapter 2: Conceptual Framework

Radcliffe and Lee (1989) argued that a novice designer should be given explicit guidance on a systematic approach to design, but this framework should be adaptable as the designer matures and becomes more self-aware. Through their analyses of engineering students, they developed an "idealized sequence" of design activities that students should pass through, which indicated their "design efficiency" (p. 202). The sequence included seven processes, beginning with identifying requirements of the task, through developing a preliminary layout of their chosen design. While this "ideal sequence" is what their students were measured against, only one student participant proceeded in this way. This indicated that, while educators may teach and provide the framework to engage in engineering design in a certain way, students may not follow this method; the engineering design process is fluid, and therefore, difficult to teach in a systematic way.

Matchett and Briggs detailed the design process used in their Fundamental Design Method Course (Gregory, 1966). They argued that their design method, which is primarily linear, is more than just a problem-solving procedure, but a way of working that involves awareness of one's own mental moves, abstract concepts of "good design", and the design decision process. This approach includes creating charts, sketches, and prototypes at various stages of the process, which are either used in later steps or tested for validity, but does not include much leeway for creative thinking.

One of the major setbacks to providing a model of engineering design that students must work within is that there is little opportunity to engage in creative, innovative behavior—established as a major aspect of engineering design in the previous section. Jon Liebman (1989) argued that the best method to teaching engineering was a model where students learn systematic design methods, but also engage in creative activities to inspire innovation and invention. While many view creativity as an essential skill to teach engineers as it promotes innovative solutions and problem-solving, many engineering programs face inherent challenges in teaching it due to a lack of materials, time, and instructor knowledge (Daly, Mosyjowski, & Seifert, 2014). Dixon and Duffey (1990) also noted the lack of engineering instructors “with the education and experience to teach [engineering] design” (p. 15).

In an effort to remedy the challenges to creative thinking when following a systematic method of engineering design, researchers like Hubka (1982) suggested the use of “design tactics,” which can help novices go through and engage in the engineering design process. Some of these tactics help with brainstorming and generating ideas, developing evaluation criteria and constraints, conducting research on the problem and design, modeling, and experimentation. The techniques he described, especially for idea generation, are similar to those discussed by several other researchers (Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; Radcliffe & Lee, 1989), and are common techniques to facilitate *divergent thinking*—an essential skill for innovative design in engineering (Charyton, Jagacinski, Merrill, Clifton, & DeDios, 2011; Hocevar, 1980). Radcliffe and Lee (1989) also suggested the use of “a logical methodology or strategy… an adopted working habit for approaching design tasks” and “a working knowledge of techniques such as brainstorming for the uninhibited generation of design ideas” as essential to engineering education (p. 206).

Integrating engineering with other disciplines. A second method for teaching engineering is an integrated model; integrated models of engineering education are gaining traction recently, where students are not learning from a purely scientific or industry perspective, but rather from an approach that includes both. Jamison, Kolmos, and Holgaard (2014) researched the historical roots of engineering education and identified three distinct perspectives of engineering and approaches to teaching it: (1) academic, (2) market-driven, and (3) integrative. Each of these has their own type of engineering education program, curriculum, and cultural perspectives or views. In addition, each has their own teaching methodologies that can be drawn on to create a hybrid learning environment where students in engineering learn about and act on the interactions between science, technology, and society. This viewpoint is directly in line with the integration of science, technology, society, and the environment emphasized in the *NGSS* (NGSS Lead States, 2013).

Integrating engineering with other disciplines. A third method is integrating engineering instruction with science or technology. The integration of science, engineering, and technology in K-12 classrooms has been viewed as a promising method to engage students in design activities (Moore, Tank, Glancy, & Kersten, 2015). When engineering and technology are integrated into other subjects, like science or mathematics, the concepts and skills will be necessary to create optimal solutions. This model is thought to provide teachers with an opportunity to introduce their students to engineering in multiple contexts (or courses) and to emphasize the engineering design process—a core characteristic of engineering—that engages students in “real” engineering without detailed content knowledge (Cunningham, Knight, Carlsen, & Kelly, 2007).

Capobianco, Nyquist, and Tyrie (2013) outlined seven essential features for teaching science through engineering design: (1) client-driven and goal-oriented; (2) providing an authentic context; (3) incorporating constraints; (4) using materials, resources, and tools familiar to students; (5) requiring the solution to be a product or process; (6) yielding more than one solution; and (7) involving teamwork. They highlighted teaching engineering as having a specific goal, that is often in an authentic context, and incorporating constraints in an effort to have children yield multiple solutions in the form of a product or a process. They also encouraged teamwork and utilizing resources that students are familiar with. These suggestions can be applied in most classrooms and in multiple disciplines.

While their work was primarily in elementary schools, Resnick, Ocko, and Papert (1988) were among the first to integrate engineering with computer science through the LEGO/Logo environment. This environment allows students to build a mechanism out of LEGO blocks and connect it to a computer where they are encouraged to use the Logo programming language to make their mechanism do what they want. Resnick and colleagues argued that the LEGO/Logo environment is ideal for teaching and learning modular design (constructing complex objects out of modular units) because the physical object the children make is made of small units (LEGO blocks) and the program they create in Logo is made of small units (language blocks). They also found that this environment put children in control of the design process because they were encouraged to formulate their own designs that they cared about, which was often not the case in hands-on lessons where students simply re-created someone else's experiment.

Findings like these have influenced STEM-focused high schools, like San Diego's High Tech High, to put an end to the divisions between subjects and science disciplines, and instead, favor project learning that encompasses multiple subjects, technology, and involves the community and local businesses. In an interview, a teacher at High Tech High stated, "When students see the interconnectedness of the subjects they're learning, they feel it's more relevant, more meaningful, and more authentic than if they're working in isolation" (Rubenstein, 2008). An example of a course that High Tech High integrated is a biology course on conservation forensics using DNA barcoding, where the five-week course consists of a single project. This kind of course integrates multiple subject areas, disciplines of science, and incorporates technology, the environment, and the community—all of which are part of the *Next Generation Science Standards* as goals for science education at the high school level (NGSS Lead States, 2013).

Engineering collaboration and competition. A fourth method used to teach engineering design is through encouraging collaboration or competition between students, groups, or schools. The role that students and student groups play in the engineering classroom is also an important teaching method for engineering, although there are conflicting ideas on this topic. Many have found that having students work together collaboratively can help facilitate problem solving and that sharing ideas and perspectives can generate more thorough or inventive solutions. The contrasting viewpoint encourages students to engage in friendly competition, either individually or in teams. This method is thought to motivate students to generate ‘better’ solutions than their competition and is more in line with the type of engineering done in a professional setting where one must solve the problem better and faster than other companies.

Capobianco, Nyquist, and Tyrie (2013) recognized the need for teamwork in their essential features for teaching science through engineering design. The Design Council (2015), an organization in the UK that researches design, developed guidelines on how to run design workshops at the secondary school level, which includes ten steps. Their method led the students through their “double diamond design method” as a whole class, where the solution was created as a *group*. The double diamond method includes sequences of divergent and convergent thinking where students generate multiple ideas or possible solutions, then narrow down or refine those for the goal of creating one solution that solves the given problem. Radcliffe and Lee (1989) also suggested that engineering education foster students to develop skills to develop and communicate designs (including sketching, CAD, and other communication skills) and the need for students to collaborate with “colleagues, experts, and available technical information instead of being confined to their own knowledge and experience” (p. 206).

A major component of the learning environment at San Diego’s High Tech High is their emphasis on collaboration and encouraging contributions from students to empower them to become active agents in their learning. One teacher stated that at High Tech High, they “let kids connect with each other and each other’s work” and emphasized how this was an important aspect of preparing students for 21st century learning (Kopietz, Harrington, & Lodaya, 2013). In an example of a high school class at

High Tech High, students worked in groups to develop their own approach to the overarching project goal and then explored ways to do it more cheaply and efficiently—a key tenant to engineering design (Rubenstein, 2008).

Other researchers suggest the use of design *challenges*, such as designing and testing a bridge, to teach engineering in the classroom (Sadler, Coyle, & Schwartz, 2000). They suggest that creating competing teams that solve the same design task will motivate students to make connections between science concepts and solutions to real world problems. Many are familiar with the iconic “egg drop” engineering project that schools have widely used for many years. This project gives individuals or groups of students the task of developing a system that will prevent an egg from breaking when dropped from a high place. While students are motivated intrinsically to simply solve the problem and make sure their egg does not break without regard for the other students’ or groups’ failure or success, there is also an element of competition between individuals or groups. Students typically want to make sure that their egg is not the one that breaks when others’ do not. This thought in the back of their mind motivates them to develop an even better solution and work harder to make sure that they do the best job possible.

Teaching guidelines for engineering design. As described previously, authors of the *Next Generation Science Standards* (NGSS Lead States, 2013) developed a set of standards for engineering design at the multiple grade bands: K-2, 3-5, 6-8, and 9-12. These standards include three to four *performance expectations* for students to demonstrate understanding of engineering design at their grade band level (Table 2c). These performance expectations were developed using the *science and engineering* *practices* (SEPs), *disciplinary core ideas* (DCIs) for engineering, and *crosscutting concepts* (CCCs) from *A Framework for K-12 Science Education* (NRC, 2011). Teachers can and will be expected to use these standards to ensure that their students are engaged in and understand the practices, process, and applications of engineering.

Table 2c

Engineering Design Standards from the NGSS

Kindergarten – 2nd Grade	
K-2-ETS1-1	Ask questions, make observations, and gather information about a situation people want to change to define a simple problem that can be solved through the development of a new or improved object or tool.
K-2-ETS1-2	Develop a simple sketch, drawing, or physical model to illustrate how the shape of an object helps it function as needed to solve a given problem.
K-2-ETS1-3	Analyze data from tests of two objects designed to solve the same problem to compare the strengths and weaknesses of how each performs.
3rd – 5th Grade	
3-5-ETS1-1	Define a simple design problem reflecting a need or a want that includes specified criteria for success and constraints on materials, time, or cost.
3-5-ETS1-2	Generate and compare multiple possible solutions to a problem based on how well each is likely to meet the criteria and constraints of the problem.
3-5-ETS1-3	Plan and carry out fair tests in which variables are controlled and failure points are considered to identify aspects of a model or prototype that can be improved.
Middle School	
MS-ETS1-1	Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.
MS-ETS1-2	Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.
MS-ETS1-3	Analyze data from tests to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.
MS-ETS1-4	Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.
High School	
HS-ETS1-1	Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.
HS-ETS1-2	Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.
HS-ETS1-3	Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics, as well as possible social, cultural, and environmental impacts.
HS-ETS1-4	Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.

Engineering, technology, and applications of science (ETS) standards from the *Next Generation Science Standards* (NGSS Lead States, 2013)

Chapter 2: Conceptual Framework

While the standards identified in the *NGSS* are the basis for teaching engineering in K-12 currently, others have developed more detailed guidelines and helpful tools for teaching engineering design, specifically at the K-12 level. Crismond and Adams (2012) developed *key performance dimensions* of engineering design that teachers can use to help inform if their students are engaging in engineering design, similar to the *performance expectations* established in the *NGSS*. The seven key performance dimensions that Crismond and Adams set forth are as follows:

- *Learning while designing*: Learn by doing; from brainstorming and prototyping; by iteration and from feedback and failure; by noticing and trouble-shooting; by drawing and dialoging with ideas, materials, and people; and from reflection.
- *Making and explaining knowledge-driven decisions*: Use understandings of physical laws, how things work, methods of construction, and insights from experiments and revisions made during the design process to help make and explain design decisions.
- *Working creatively to generate design insights and solutions:* Design should be informed by creative insights that get generated when framing a problem, generating potential solutions, and proposing novel ways to trouble-shoot and iteratively improve prototypes. Students should learn to deal with uncertainty and take productive risks while working with their ideas in creative ways.

- *Perceiving and taking perspectives intelligently:* Use empathy when imagining the experiences of products from the view-points of a wide variety of users, and learning what to focus on and what is relevant in order to detect positive and negative product performance.
- *Conducting sustained technological investigations:* Collect organize, and analyze evidence; develop critical standards for performing technological investigations; and evaluate critical questions related to the device or system they are developing.
- *Using design strategies effectively:* Know when and how to use design practices and strategies to accommodate constraints of time and budget. Work effectively in groups and deciding which information and past experiences to draw upon and apply most effectively when addressing problems.
- *Integrating and reflecting on knowledge and skills:* Combine skills in design and fabrication with formal and everyday understandings of relevant disciplines to create technological solutions.

Crismond and Adams (2012) also laid out the Informed Design Learning and Teaching Matrix, which was intended "to help teachers do informed teaching with [engineering] design tasks while developing their own design pedagogical content knowledge" (p. 739). This matrix also discussed the upper and lower anchor points for each of the strategies of engineering design. They argued that these engineering design strategies are observable and teachable by instructors and can be used as an assessment tool to determine a student's design proficiency. The corresponding anchor points were provided to give practitioners an idea of what is to be expected of students at the beginning and end of the engineering design education spectrum. They also provided examples of each for beginning and informed designers, learning goals of informed designers, and examples of teaching approaches to help students reach the design objectives.

Summary. While much of the traditional methods for education in engineering design take into account essential functions of engineering practice, such as materials selection, production, reliability, and maintenance, this is not as much of a concern in the K-12 education setting where students are not designing with the end goal of making a product that will go into mass production. Some researchers have examined the preparedness of the United States for the implementation of the *Next Generation Science Standards* by analyzing existing engineering education standards and frameworks in the states (Carr, Bennett, & Strobel, 2012; Moore, Tank, Glancy, & Kersten, 2015). While they have found that some states have set up solid frameworks that incorporate engineering into their K-12 education systems, still many states have limited or no engineering content or practices prior to the *NGSS*.

Despite this, research has already shown that integrating engineering design into science curricula has a benefit not just on the engineering abilities of students, but also on students' science content performance (Wendell & Rogers, 2013). Results like this demonstrate the importance of including engineering and engineering design specifically into the nation's science standards. While the benefits of design to students are clear, further study on how teachers conceptualize engineering design needs to be done. If teachers and instructors are not comfortable or competent in what engineering design is then their students will be less likely to benefit from these concepts.

In an effort to determine how teachers at multiple stages along the learning to teach continuum understand and conceptualize engineering design, this study examined concept maps and interviews that elicited prospective, preservice, and practicing teachers', as well as teacher educators' thoughts on engineering design. A brief description of each of these teacher groups is provided below.

The Learning-to-Teach Continuum

The learning-to-teach continuum (as described by Feiman-Nemser, 1983) includes four major phases: (1) the pretraining phase, (2) the preservice phase, (3) the induction phase, and (4) the inservice phase. Each of these phases corresponds to a group of teachers that fall along this continuum. While these phases along the learning-to-teach continuum roughly correspond to the groups of participants in this study, because they do not align perfectly I chose to rename the teacher groups to more closely align with the participants in this study. It is important to examine each of these groups of teachers in an effort to get an integrated understanding of the ideas that are held by all secondary teachers along the entire continuum. I briefly describe each group of teachers that were participants in this study, and identify and provide reasoning for where they fall along the learning-to-teach continuum. Teacher educators do not fall within the description of the learning-to-teach continuum provided by Feiman-Nemser (1983), but since they play an important role with teachers along this continuum they are included as a separate group in this study.

Prospective Teachers

Teachers that are in the “pretraining phase” (Feiman-Nemser, 1983) of the learning-to-teach continuum include those who are learning things that have the potential to shape their future teaching, whether or not they decide to eventually become teachers. This group is often referred to as prospective teachers, or potential teachers, because there is a possibility that they may become teachers, but there is no guarantee or commitment on their part yet. Because those who do become teachers can come from any field of study at the undergraduate level, and because engineering is relatively new in the arena of K-12 education, it is difficult to find research that has examined this group of teachers specifically addressing engineering.

Individuals in this study who were classified as prospective teachers included those who were currently undergraduate students in an unrelated field to education, but participated in an internship experience with the university’s education department where they learned about teaching science and engineering at the high school level and participated in a local high school classroom. While some of these undergraduates may have gone on to pursue teaching, others did not.

Preservice Teachers

Teachers that are in the “preservice phase” (Feiman-Nemser, 1983) of the learning-to-teach continuum include those who are future teachers that are undergoing formal teacher education and preparation—usually through a college or university teacher education program. This group is usually referred to as preservice teachers since they are part of preservice teacher preparation. Unlike prospective teachers, preservice teachers have made a commitment to teach by enrolling in a teacher preparation program or undergoing other formal training to teach.

While some research has examined preservice teachers in K-12 engineering education contexts (Bers, Ponte, Juelich, Viera, & Schenker, 2002; Fantz, De Miranda, & Siller, 2011), there is still much to learn about this group. The preservice teacher group that participated in this study consisted of individuals who were enrolled in a university teacher education program for secondary science teaching. These teachers took multiple courses in education and teaching, as well as content specific courses in science and engineering, and engaged in student teaching at local middle and high schools throughout the year.

Practicing Teachers

Teachers that are in the “induction” and “inservice” phases (Feiman-Nemser, 1983) of the learning-to-teach continuum include those who are practicing teachers who have completed their formal teacher training. For this study, I did not make a distinction between practicing teachers who had and had not completed an induction program for beginning teachers. Rather, all teachers who had completed formal teacher training and were teaching classes regularly were part of the practicing teachers group. This group included teachers who were just starting out (first-year teachers) and those who had been teaching for decades.

Chapter 2: Conceptual Framework

Much research has already been conducted on practicing teachers and their views of and practices in teaching engineering in the K-12 context (Daugherty, 2009; Gattie & Wicklein, 2007; Hsu, Purzer, & Cardella, 2011; Hynes, 2012; Rogers, 2005; Rogers, 2006; Rogers & Portsmore, 2004; Fantz, De Miranda, & Siller, 2011; Yasar, Baker, Robinson-Kurpius, Krause, & Roberts, 2006). However, most of this research is related to their familiarity with the content, their specific teaching methods, or their professional development around engineering—not on investigating their understandings of the concept of engineering design specifically.

Teacher Educators

Teacher educators are not part of the learning-to-teach continuum as defined by Feiman-Nemser (1983), however, they influence the individuals who fall along that continuum. Teacher educators are individuals who instruct prospective, preservice, and sometimes practicing teachers on teaching methods, general education research and theory, content-specific pedagogy, and many other aspects of formal teacher education.

Individuals who were part of the teacher educator group in this study included those who were instructors or faculty at a university teacher education program and actively provided instruction and guidance to prospective and preservice teachers and had strong relationships with practicing teachers as well. Because engineering is so new to teacher education widely, there are no studies of note yet that look at university teacher educators specifically for engineering.

Chapter 3: Method

This chapter lays out the theoretical perspective used to guide this study overall—phenomenography—and provides an overview of the study's context, participants, data collection methods, and analyses. I begin with an overview of relevant literature on phenomenography because this theory guided both the methodologies selected and the methods used. This section is important because it provides a solid foundation on which this study rests—supported by decades of systematic research. The Study Context section includes discussion of the larger research context in which this study was situated, as well as the schools that served as sites for research. The Participants section describes in detail the three groups of teachers (along the learning-to-teach continuum) as well as the teacher educators and how they were selected for inclusion in this study.

Because a phenomenographic study relies on eliciting a great deal of information from each participant in order to paint an accurate picture of an individual's perceptions of concepts, the particular methods used in data collection are explored in detail in the Data section. The last sections detail the methods used for analysis. Analyses consisted of three separate levels, each following the series of steps laid out by phenomenography. The first level involved sorting through all of the data to identify the many aspects of engineering design discussed by participants. The second involved sorting through those aspects to define categories of description for engineering design. The last level involved looking at these categories of engineering design from multiple perspectives, including through the lenses of experience and demographics.

Chapter 3: Method

Phenomenography as a Guiding Theory

Guiding this study was a theory, phenomenography, that states that a certain phenomenon or concept can be thought of differently depending on how a person perceives or experiences it (Marton, 1981). Phenomenography argues that concepts, such as engineering design, can only be understood in a finite number of different ways, and this study seeks to determine the different ways that are perceived by the participants across the learning-to-teach continuum. This theory posits that one can go through a series of systematic steps as an approach to tease out the various contrasting aspects of the larger concept—engineering design in this case—and use these to develop categories of meaning that highlight the variation in conceptual understanding. These categories exemplify some, if not all, of the different ways that engineering design can be understood. In this section, I describe phenomenography as a theoretical perspective that I used to guide this research. Later, I describe the specific methods from phenomenography that guided my analysis of data.

Phenomenography emerged as a qualitative research approach in Sweden in the 1970s and was first formally described by Marton in 1981. He explained that with this research approach the aim is to learn about how people perceive, experience, or conceptualize a certain aspect of reality or a phenomenon. Phenomenography posits that "each phenomenon, concept, or principle can be understood in a limited number of qualitatively different ways" and that the researcher is tasked with uncovering and mapping these differences into conceptual categories (Marton, 1986, p. 31). Because phenomenography is a whole research approach, it includes a theoretical foundation as well as established methodologies.

In 2011, Case and Light published an article on the “Emerging Methodologies in Engineering Education Research,” which provided an overview of phenomenography and served as an exemplar paper in the field. Shortly after that, Daly, Adams, and Bodner’s (2012) phenomenographic study on how professional designers “experience, give meaning to, and approach design” (p. 187) became the exemplar of how to use a phenomenographic approach in engineering education. Daly and colleagues looked at how individuals across disciplines experience and understand design by creating an outcome space that consisted of six qualitative distinct viewpoints. They posited that these perceptions of design may influence individuals’ design approach and how design can be facilitated by finding common ground if the multiple “design lenses” are recognized (p. 187). After these two articles, phenomenography quickly became a well-regarded qualitative methodology in the field of engineering education (Baillie & Douglas, 2014).

In phenomenographic studies, the goal is to create an “outcome space” that captures the essence of the various ways individuals can experience, understand, and conceptualize “phenomena or aspects of a phenomenon (such as specific concepts)” (Case & Light, 2011, p. 199). In order to discern this outcome space, phenomenography relies on methods such as conducting interviews and utilizing associated materials (such as textual and/or visual materials) to aid researchers in understanding participants’ conceptions at a deeper level. The methods that guide phenomenographic research are the underpinnings of this study, which sought to uncover the various conceptions and understandings of engineering design held by teachers along the learning-to-teach continuum.

Research Questions

The following questions guided this study: (1) What conceptions of engineering design did teachers along the learning-to-teach continuum hold? (2) What characteristics or experiences of participants appeared to influence their understanding of engineering design, such as their engineering experience, other STEM experiences, or personal background? The context of the study, the methods used to collect data to answer these questions, and the analyses conducted are detailed below.

Study Context

The context for this study was two scholarship programs for prospective and preservice teachers. Each scholarship program consisted of a field placement at a local high school—in one of two science, technology, engineering, and mathematics [STEM]-related academies or in a regular science classroom—and seminars or formal coursework through a university teacher education program. There were 27 total participants: nine undergraduate, prospective teachers; eight post-baccalaureate, preservice teachers enrolled in a teacher education program [TEP]; seven practicing teachers from local high school STEM-related academies; and three teacher educators who served as instructors in TEP.

The first scholarship program, Physical Science and Engineering Teaching [PSET], was in its third year of implementation and geared towards physical science and engineering prospective and preservice teachers. During the 2015-2016 academic year, all prospective teachers were part of the PSET program, as were three of the preservice teachers. The other scholarship program, Science for English Language Learners [SELL], was in its first year of implementation and attempted to better support preservice science and mathematics teachers in learning to teach ELLs. The remaining five preservice teachers were part of the SELL program. Because this program also included preservice mathematics teachers, there were two individuals who participated in the same rounds of data collection as part of another project, but because this study focused only on science, they were not included here. The practicing teachers and teacher educators mentored or instructed those participating in both programs.

Table 3a

Participant Groups by Study Context

	Participant Group			
Context	*Prospective Teachers*	*Preservice Teachers*	*Practicing Teachers*	*Teacher Educators*
University TEP	9	8	N/A	3
Engineering Academy (PBEA)	5	2.5*	5	N/A
Eco Academy	4	N/A	2	N/A
Traditional High School#	N/A	5.5*	N/A	N/A
Middle School	N/A	1	N/A	N/A

N/A = Not Applicable
*One preservice teacher was placed at PBEA half of the year, and a traditional classroom the other half.
#Preservice teachers who were placed at a traditional high school at least half of the year (either semester).

Practicing teachers mentored the prospective and preservice teachers as they participated in their classroom—by observing, working with individual or small groups of students, and/or teaching lessons. Teacher educators taught the prospective and preservice teachers about science and engineering education, best teaching practices, effective instruction for ELLs, and other education content at various points throughout the two programs. Many preservice teachers also spent at least part of their time in a middle school classroom to experience all secondary science contexts (see Tables 3a above, and 3b below).

School Placements

As introduced above, during the 2015-2016 academic year, prospective and preservice teachers participated in field placements at local secondary schools as part of these two scholarship programs. These field placements were primarily at two local high school that had STEM-related academies within the larger school. This means that the high school had other academies and traditional courses in addition to these STEM-related academies. Further, many preservice teacher candidates completed their field placement experiences at multiple secondary schools; they did not spend the entire year at one school site. As such, some participants in this study participated for part or all of the year in classes that were not associated with these two STEM-related academies. Table 3b provides a breakdown of the school context(s) where teachers participated. A description of each type of field placement is provided below.

Project-Based Engineering Academy. An engineering-focused academy at a local high school, Pueblo High School [PHS], served students in grades 9-12 with approximately 100 students in each grade level. Students at the Project-Based Engineering Academy [PBEA] were admitted into the program in grade 9 through a competitive application and interview process and then continued in the academy as a cohort through grade 12. A team of PBEA teachers collaboratively designed and implemented the curriculum used to teach students engineering. The curriculum was organized around completion of authentic engineering projects with an emphasis on Science, Technology, Engineering, Art, and Mathematics (STEAM). Instruction in the academy spanned physics, computer-aided design (CAD), art, and machining; each subject was housed in its own dedicated classroom, or “space.” A different credentialed teacher taught each of these four subjects and students rotated through the physics, CAD, art, and machining subject matter spaces multiple times throughout the academic year. Individual projects in grades 9 through 11 (e.g., a mobile, a light box sculpture, and a Moiré kinetic light sculpture) prepared students for a collaborative senior capstone project. Students completed their other classes at the adjoining high school.

The Eco Academy. An environmental education-focused academy at another local high school, Mission High School [MHS], offered students a series of courses related to environmental science issues, including Green Chemistry and Green Engineering. The Eco Academy [EA] was a less formal program than PBEA: There was no application process and courses were open to all of the high school’s students. In Green Chemistry, environmental issues (e.g., climate change, oil spills) were incorporated into a traditional chemistry curriculum. In Green Engineering, students engaged in environmentally focused engineering projects (e.g., creating a toy solar-powered car). The practicing teacher who taught Green Engineering also taught physics courses that prospective and preservice teachers participated in. These physics classes were not part of the academy, although participants spent considerable time in those classes.

Other school placements. As stated above, some preservice teachers were not placed in either of these two STEM-related academies. Rather, they were placed in a traditional science classroom at a local secondary school. Because the teacher education program usually required separate placements in fall and winter semesters (they follow the local K-12 school year), some preservice teachers were at different schools for each. Some preservice teachers were placed at the high schools that house the two academies (Mission High School and/or Pueblo High School) in traditional science classes (e.g., biology, chemistry, or physics). Other preservice teachers were placed in traditional science classrooms at San Mateo High (SMH), a third local high school, or at one of three local junior high schools—Calle Middle School (CMS), Orange Grove Junior High (OGJH), or Mission Middle School (MMS)—in a 7th or 8th grade science classroom focused on life science or physical science (see Table 3b).

Table 3b

Preservice Teacher Field Placement by Semester

Preservice Teacher	**K-12 School Semester**	
	Fall	*Spring*
Molly	Mission High School	Orange Grove Junior High
Kari	San Mateo High	Calle Middle School
Adam	Orange Grove Junior High	Pueblo High School
Caitlyn	Project-Based Engineering Academy	Project-Based Engineering Academy
Sasha	Mission High School	Mission High School
Kayla	Pueblo High School	Project-Based Engineering Academy
Haylee	Project-Based Engineering Academy	Project-Based Engineering Academy
David	Calle Middle School	Calle Middle School

Programs of Study

Undergraduate internships. The nine prospective teachers participating in this study were part of an undergraduate internship, which was the undergraduate component of the PSET scholarship program described above. Originally, 12 prospective teachers agreed to participate in the study, but three did not complete the required data collection or field placements during the academic year. This undergraduate internship consisted of a five-week intensive summer experience in high school STEM-focused academy classrooms as well as seminar sessions led by university teacher educators. After this summer experience, prospective teachers continued participating in the academy classrooms for at least one quarter, but received no more formal instruction from teacher educators.

Table 3c

Prospective Teacher Hours of Participation in Classrooms During Academic Year

Name	School Academy	Engineering	Quarter	Hours
Saul	EA	Yes	Fall 2015	46
			Winter 2016	36
			Spring 2016	25
Ralph	EA	Yes	Fall 2015	10
			Winter 2016	17
			Spring 2016	35
Nick	PBEA	Yes	Fall 2015	45
			Winter 2016	22.5
Monty	PBEA	Yes	Fall 2015	45
			Winter 2016	26.5
Zeb	PBEA	Yes	Fall 2015	30
			Winter 2016	6
Xandra	EA	Yes	Spring 2016	27
Rick	EA	No	Spring 2016	12
Carlos	PBEA	Yes	Fall 2015	35
Anthony	PBEA	Yes	Fall 2015	62

More specifically, because the academic year at the university where the prospective teachers were enrolled began instruction five weeks after instruction at the local high schools, prospective teachers participated in high school classes all day, five days a week, for five weeks. Prospective teachers also attended a weekly seminar during this summer internship, where they discussed their experiences in classrooms and received introductory instruction on ways to effectively teach science and engineering to secondary students.

Prospective teachers in this study also continued their participation in the STEM-related academy classrooms throughout the rest of the academic year. Because they were taking university courses during this time, their participation in classrooms ranged from 6 to 62 hours per university quarter. Some participated in one or two quarters, but could not participate in all three quarters due to scheduling conflicts or other factors. Table 3c shows the number of hours in the classroom each prospective teacher participated in during the academic year (fall, winter, and spring quarters).

Preservice Teacher Education Program. Preservice teachers were enrolled in a 13-month post-baccalaureate teacher education program [TEP] to earn their teaching credential in science and/or engineering, and if they chose to do so, a master's degree in education (M.Ed.). During the first summer of the program, preservice teachers took an introductory course in science education from the three teacher educator participants and other courses related to teacher education, but had no experiences in the classroom.

Their classroom placements were in line with the semester system of the K-12 schools they were placed in (see Table 3b above), however, the fall "semester" did not begin until partway through the K-12 semester, to better align with their TEP courses, and rather corresponded more closely with the fall quarter of the university. In the fall quarter, they participated in science or engineering classrooms at local secondary schools in the mornings and completed coursework at the university in the evenings. During the winter and spring quarters (or the full K-12 spring semester), they became the instructor of record for one class period, as well as continued taking university courses in the evenings.

The three science and engineering education methods courses and yearlong professional issues course preservice teachers received were taught by the three teacher educators who participated in this study and covered various topics related to the teaching and learning of science and engineering at the high school level. For their student teaching component of TEP, preservice teachers were placed in secondary school classrooms in a variety of settings. Two of the preservice teachers were part of the PSET scholarship program and were thus placed at the high school engineering academy (PBEA). The five preservice teachers who were part of the SELL program were placed in traditional science classrooms at local high schools, with one being placed at a middle school for the entire year. The final preservice teacher was also part of the PSET program and was placed in a traditional classroom for half of the school year and placed at PBEA for the remainder of the year.

Participants

Study participants are grouped depending on where they fell along the learning-to-teach continuum described in more detail in Chapter 2. The groups of participants included the following: (1) prospective teachers, (2) preservice teachers, (3) practicing teachers, and (4) teacher educators. The size and demographic makeup of these groups varied, as did their activities and instruction throughout the study—which was discussed in detail above. Table 3d provides an overview of the participants, their associated teacher group, the scholarship program they were part of, field placement assignment(s), and demographic information.

Table 3d

Overview of Study Participants

Group	Name	School	Engin-eering	Gender	Ethnicity	Major
Prospective	Zeb	PBEA	Yes	M	European American	Physics
Prospective	Xandra	EA	Yes	F	Latino/a	Physics
Prospective	Saul	EA	Yes	M	Asian American	Physics
Prospective	Rick	EA	No	M	Latino/a	Chemistry
Prospective	Ralph	EA	Yes	M	Asian American	Electrical Engineering
Prospective	Nick	PBEA	Yes	M	European American	Biochemistry
Prospective	Monty	PBEA	Yes	F	European American	Chemistry
Prospective	Carlos	PBEA	Yes	M	European American	Physics
Prospective	Anthony	PBEA	Yes	M	European American	Physics
Preservice	Molly	MHS	No	F	European American	Biology
Preservice	Kari	SMH	No	F	European American	Anthropology
Preservice	Adam	PHS	No	M	European American	Biology
Preservice	Caitlyn	PBEA	Yes	F	European American	Engineering Physics
Preservice	Sasha	MHS	No	F	European American	Computer Science
Preservice	Kayla	PBEA	Yes	F	European American	Physics
Preservice	Haylee	PBEA	Yes	F	European American	Physics
Preservice	David	CMS	No	M	Asian American	Biology
Practicing	Ken	PBEA	Yes	M	European American	Physics
Practicing	Kurt	PBEA	Yes	M	European American	Electrical Engineering
Practicing	Dana	PBEA	Yes	F	European American	Chemistry
Practicing	Josh	PBEA	Yes	M	European American	--
Practicing	Kristy	PBEA	Yes	F	European American	--
Practicing	Macy	EA	Yes	F	European American	Physics
Practicing	Sandra	EA	No	F	European American	--
Educators	Sally	TEP	Yes	F	European American	Biology
Educators	Patty	TEP	Yes	F	European American	Environmental Science
Educators	Jasmine	TEP	Yes	F	European American	Biology

-- = Demographic data was not collected from practicing teachers or teacher educators. Information for them is provided if voluntarily given during their focus group interview or in follow up discussions.

Prospective Teacher Participants

All 12 undergraduate, prospective teachers involved in the 2015-2016 PSET scholarship program agreed to participate in this study; as stated above, however, three did not complete the data collection process. Of the nine participants presented in this study, then, five prospective teachers were placed at the Project-Based Engineering Academy [PBEA] and four were placed at the Eco Academy [EA]. Table 3d shows the demographic information for these nine prospective teacher participants. Having an undergraduate major or expected major in the physical sciences, computer science, or engineering was required to take part in the PSET program.

It is important to clarify that the five prospective teachers placed at PBEA participated in all aspects of the academy’s integrated STEAM curriculum for grades 9, 10, and 11. Thus, they were exposed to all four spaces (physics, CAD, art, and machining) and interacted with all four practicing teachers. In addition, during the academic year, they had the opportunity to work with the grade 12 students on their capstone engineering projects. For the four prospective teachers placed at EA, three were placed in physics and Green Engineering classes with one practicing teacher, and one was placed with a second practicing teacher in Green Chemistry classes. All of these prospective teachers continued to participate in classrooms throughout the academic year (September-June) to varying degrees (shown in Table 3c above).

Preservice Teacher Participants

All eight preservice science teachers who were part of either the PSET or SELL scholarship programs during the 2015-2016 year agreed to participate in this study. These preservice teachers were enrolled in a fifth-year, post-baccalaureate teacher education program [TEP] at the same university where the undergraduate prospective teachers were enrolled. Three of the preservice teachers were pursuing credentials in physics, and/or engineering; the other five preservice science teachers were pursuing credentials in biology. Three of the preservice teacher participants completed student teaching field experiences in academy classrooms at PBEA. Demographic information for the preservice teachers is also shown in Table 3d.

Practicing Teacher Participants

All six practicing teachers from the two high school academies (PBEA and EA) agreed to participate in this study. At PBEA, there were four practicing teachers, one for each space (Ken in physics, Dana in art, Kurt in CAD, and Josh in machining) and a fifth teacher, Kristy, who formerly taught in the physics space and was now a coordinator for the academy. Due to the integrated nature of PBEA, all practicing teachers worked with all prospective teacher participants. The three preservice teachers placed at PBEA, however, worked primarily with Ken, the physics teacher.

At EA, there were two practicing teachers who participated in this study. One teacher, Macy, taught the physics and Green Engineering courses; the other, Sandra, taught the Green Chemistry classes. Macy mentored three prospective teachers, while Sandra mentored one prospective teacher who participated in this study. Information on all practicing teachers is provided in Table 3d. Additional demographic information on practicing teachers was not collected.

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Teacher Educator Participants

Three teacher educators from the university in which the scholarship programs were housed agreed to participate in this study. All three teacher educators taught science education courses to the preservice teachers, and two of them also worked closely with the prospective teachers. All three of the teacher educators had a background in the biological sciences and regularly taught courses in the teacher education program [TEP] to secondary science preservice teachers. Information on these teacher educators is also provided in Table 3d. Additional demographic information on teacher educators was not collected.

More specifically, one teacher educator, Jasmine, was the director of the scholarship programs, where she worked closely with both prospective and preservice teachers in this study. She also taught courses in science education in TEP to preservice teachers. Another teacher educator, Patty, was the secondary science teaching content supervisor for TEP, and thus, taught and mentored all of the preservice teachers. Patty did not work with any of the prospective teachers. The last teacher educator, Sally, was the academic coordinator for the two scholarship programs and a lecturer in science education for TEP. Sally led the seminar sessions taken by the prospective teachers, as well as taught courses in science education and mentored the preservice teachers.

Researchers

A total of seven researchers were involved in this study. All seven researchers participated in the data collection phase: the project's principal investigator, evaluator, and five science education graduate students. All researchers in this phase collaborated to create interview protocols, schedule interviews, and conduct interviews with the participants. As a member of this team, I developed the engineering-related interview questions and concept map instructions and conducted a majority of the interviews of undergraduate, prospective teachers as well as all practicing teachers. I was the only team member who also continued with the analysis phase of this study.

Data Collection

In this study, concept maps were used in conjunction with semi-structured interviews to elicit participants' ideas, understandings, and overall conceptions about engineering design. Concept maps are diagrams that demonstrate visually the way someone conceptualizes a main topic by organizing related terms in a meaningful way and creating connections that show the relationship among multiple terms (Novak & Gowin, 1984). These diagrams can be constructed in multiple ways for many different purposes and have been used by teachers in classrooms to elicit students' conceptions, as well as by researchers on a variety of topics. It is thought that to get a deeper understanding of an individual's conceptions on a topic one should also interview her or him about it. Using concept maps alongside interviews is a method that can provide insight into the various ideas participants have on a topic. It is utilized by many researchers, including phenomenographers.

Concept maps were used in this study to elicit participants' understandings of the engineering design process through examining the way they organized keywords and made connections between them. After participants constructed concept maps on engineering design, these maps were used as an interview tool to prompt further elaboration of their ideas and understandings—a technique used by many researchers and explained in more detail below. In an effort to explain the rationale behind using these methods for data collection, I begin by providing an overview of how concept maps can be used in qualitative education research—including being used alongside interviews—and then detail more thoroughly how these methods were used in this study.

Concept Maps and Interviews

Concept maps can be used in many ways by students, teachers, and researchers alike. Novak and Gowin (1984) noted that concept mapping is a remarkable tool that taps into the human capacity for pattern recognition in images and provides a method for learning and eliciting understanding far superior to rote recall or traditional methods used to assess student understanding. Daley (2004) claimed that concept maps were a key strategy in qualitative research because they helped the researcher focus on *meaning*. Two main ways to use concept maps relevant to this study are described in more detail in the following sections. In the first method, concept maps are used to construct the ideas and understandings of an individual visually. In the second method, concept maps are used by researchers as an interview tool to elicit further discussion of these ideas and understandings.

Concept maps to elicit understanding. Concept maps were invented as a way to elicit understandings in a more meaningful and reliable way than traditional methods—such as writing. Concept maps are also based on a strong theoretical foundation in learning theory, which claimed to better represent a person’s knowledge. In this section, I first provide the theoretical foundations and rationale for the use of concept maps. I will then discuss how concept maps are constructed and the various ways they can be used to elicit participants' understanding.

Theoretical foundations of concept maps. Novak (1980) was the first to discuss using concept maps in science education. He discussed how the chunking of information into related groups could be facilitated for students if concepts could be tied together meaningfully. Based on theories of information processing, this chunking of information could help students store more concepts in their short-term memory, and hopefully, transfer them into long-term memory. This is important for education because educators want students to learn information thoroughly, which means storing it in their long-term memory, and any strategy that could help facilitate this should be utilized.

To provide a strong theoretical basis for the use of concept maps in education, Novak drew on Ausubel's (1963) theory of *meaningful learning* (as cited in Novak, 1980). He stated that "meaningful learning occurs when new knowledge is consciously linked by the learner to existing concepts or propositions the learner already knows" (p. 282). He later discussed the theoretical and epistemological underpinnings of concept mapping in more detail as well as identified the multiple ways that concept maps could be used in a variety of contexts, including teacher education, instructional design, and exploring meaning frameworks (Novak 1990; Novak & Canas, 2008).

Rationale for concept maps. A study of high school students (Edwards & Fraser, 1983) found that traditional methods for assessing student understanding, such as asking them to write about a topic, may not provide an accurate representation of their true understandings of that topic for multiple reasons. First, students tended to have difficulty expressing their ideas clearly in the written form. In interviews conducted after the students had written about the topic, inconsistencies were found between what the students had written and what they expressed in the interview. A majority of these inconsistencies involved conceptions that seemed either unclear, incomplete, or demonstrated only partial understanding of the topic in the students' writing, that, upon discussing more fully in the interview, were now revealed to be either completely correct or incorrect.

Additionally, Edwards and Fraser (1983) noticed that a significant portion of students' writing had not been correctly interpreted by the reader, and this again came to light through interviewing the students. This finding suggested that teachers who are reading students' responses may have trouble accurately interpreting what is written and may thus conclude that the student does or does not understand a concept, when in fact the opposite is correct. The results from this study exemplified that written responses alone are not good indicators of students' cognitive structures. Instead, the authors proposed using concept maps to elicit these cognitive structures to assess understanding of a topic.

Creating concept maps. Drawing on the above theoretical framework, Novak and Gowin (1984) argued that learned concepts can be labeled with words (e.g., the concept of a dog can be labeled 'dog') and linked together to show the relationships between multiple concepts through the construction of *concept maps*. *Concepts* are defined as "the regularity in events or objects designated by a sign or symbol," such as dog, chair, or thunder (p. 283). Two or more concepts can be liked into *propositions,* or "semantic units" (Novak & Gowin, 1984, p. 15), that clarify the relationships between them. For example, in the sentence 'grass is green,' the two *concepts* 'grass' and 'green' are linked together with 'is' to create a *proposition*. Increasing the number of propositional statements that include a particular concept leads to increased meaning and precision of meaning for that concept; the more links to a concept, the greater the understanding of that concept. Concept maps demonstrate these understandings visually.

Students in traditional education settings may be more familiar with writing or verbalizing their thoughts and understandings of a topic, rather than using diagrams like concept maps to represent those conceptions. To make concept maps more accessible and more easily understood by students, Edwards and Fraser (1983) suggested that teachers relate concept maps to other diagrams that may be familiar to students, such as food webs or classification keys. According to Novak (1980), students can demonstrate concept learning by constructing concept maps, and teachers can facilitate this in the classroom by building maps "on an overhead transparency or on the chalkboard, adding related concepts and labeling the lines to form propositions" (p. 283). More detailed instruction on how to construct a good concept map, including providing a focus question, creating a "parking lot" of concepts, and generating multiple drafts of one's concept map, were discussed later by Novak and Canas (2008). They also discussed the varying methods that can be used to create concept maps, including using computer software (Novak & Canas, 2006; 2008).

Edwards and Fraser (1983) provided two different formats for constructing concept maps. The first format was more basic, and the second added a mathematical component. Format one asked students to write down six or seven key words associated with a particular topic determined by the teacher. Next, they would order these words from most to least important (or occasionally of equal importance) and put the most important words at the top and least important at the bottom. Lastly, students drew lines between words that could be related to each other and wrote linking words on those lines. This format is the basic concept map format that has been widely used in classroom and education research contexts.

The second format of concept mapping Edwards and Fraser (1983) discussed added a mathematical procedure to the ordering of the student-generated words. They asked students to rate the degree of relation between each pair of words on a 0-3 scale. The total rating for each word could be achieved by summing up all the relational ratings between it and the related words. While this format might provide more information on how students see the relationships between words, researchers found that all of the students who used this format complained about the tedium of the process involved with the mathematical procedure.

These student insights gathered by Edwards and Fraser (1983) suggested that the first format of concept mapping was better to use in the classroom setting because it allowed teachers to accurately see students’ understanding of a topic without placing too much burden on students to produce it. Novak and Gowin (1984) noted the necessity of the linking words between concepts in order to accurately assess students’ meaning through concept maps. In their early work they attempted interpreting students’ meanings from concept maps constructed without these linking words, but found this difficult and noted differences among those attempting to interpret the same map. Additionally, they discussed that sometimes arrows drawn on linking lines could be helpful to show relationships that are primarily in one direction.

Types of concept maps. Concept maps are a subcategory within the larger category of diagrams. They are typically used to gather information about a subject's knowledge or cognitive structures, to measure change over time or differences between groups, or when other data collection techniques are not conducive—due to limited time, availability, language or cultural barriers, etc. (Umoquit, Tso, Burchett, & Dubrow, 2011). Other diagrams, such as flow charts, cycle diagrams, and predictability trees, are traditionally recognized as methods to represent concepts and meanings separate from, but still related to concept maps (Novak & Gowin, 1984). It is important to add, however, that other researchers have included these types of diagrams under their definition of concept maps. Wheeldon and Faubert (2009), for example, argued that many researchers hold a rigid definition of concept maps, which was adhered to for the sake of conducting quantitative analyses (the original intent of concept mapping in research). They encouraged researchers to recognize that the flexibility in defining concept maps can greatly expand the use of them in varying research contexts to uncover participants' knowledge and understanding of a subject.

Wheeldon and Faubert (2009) provided a general definition of concept maps as a technique that demonstrates how people visualize relationships across concepts. This is very broad, encompassing diagrams such as process diagrams and flow charts that are present in this study. While many researchers will include these types of diagrams in their definitions of concept maps, they do so because they recognize the multiple structures that concept maps can display, many of which share features with these other diagrams. For example, Kinchin, Streatfield, and Hay (2010) recognized three major structures of concept maps—the spoke, the chain, and the network—which are also present in other types of diagrams. In fact, many process diagrams or flow charts are basic chains, perhaps with some added structural elements to make them more akin to networks of concepts depending on how complex the process-in-question is.

Many participants in this study tended to create concept maps that more closely resemble process diagrams of the engineering design process. While this was not anticipated by the researcher, using the more expansive, flexible definition of concept maps allows for these diagrams to be included as concept maps and for similar data collection and analysis procedures to be used regardless of how the participants understood and engaged in the concept mapping task.

Realizing concept connections. Having participants construct concept maps is beneficial because it allows them to visualize the concepts in a more abstract way and to see connections that they may not have realized before. Novak and Gowin (1984) noticed that students and teachers often recognized new concept relationships while drawing concept maps and believed that concept mapping may help foster creativity and enhance understandings. They also believed that the making and remaking of concept maps and the sharing of these maps with others could help develop reflective thinking, allowing teachers and learners to exchange views on why some aspects of a concept map are good, what may be missing, and what misconceptions may be present.

This sharing of concept maps helps to negotiate the meanings of concepts and the overall topic. This is the case, Novak and Gowin (1984) explained, because "meanings… can be shared, discussed, negotiated, and agreed upon." and that when done as a group, concept mapping can lead to "lively classroom discussion" (p. 20). Teachers can elicit what students may already know about a topic of future study by asking them to discuss what they know about it, and/or construct a concept map, and the teacher will most likely notice that students have some related concept(s) that they can anchor new information to. By utilizing this technique, teachers can create a *cognitive bridge* between the students' prior knowledge and related concepts to the new concepts that they wish to teach. Novak proposed that meaningfully learned concepts and propositions make new learning easier and easier, and thus an effort should be made to facilitate this new learning through regularly generating concept maps to help integrate prior knowledge with newly learned concepts. This integration can help create new cognitive structures that can be incorporated into long-term memory.

Concept maps for assessment. Since concept maps are commonly used to elicit ideas and understandings of individuals, they are often used as a form of assessment. Moreira (1985) argued that the primary motivations for teachers to use concept maps were as follows:

> He/she is interested in getting information about how the student structures (in the concept map) differentiates, integrates, or relates the key concepts of a given unit of study, topic, or discipline… [and] learning about students' misconceptions and about what meanings they assign to certain concepts. (pp. 159-160)

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Moreira (1985) explained that concept mapping could be used for externalizing understandings for various learning tasks -- including units of study, laboratory experiments, research papers, or works of literature -- in a wide range of disciplines and at any age. He emphasized that when concept maps were used for evaluation, they were used as a kind of formative assessment so the teacher could get an idea of where the students were and not to assign them a grade. Turns, Atman, and Adams (2000) discussed the use of concept maps as an assessment tool in engineering education. They proposed that concept maps can be utilized at the individual course level—"where the goal may be to explore what students are learning or to assign a grade"—or at the program level—"where the goal may be to explore students' conception of an overarching topic or to verify student mastery of a knowledge domain" (p. 164).

Edwards and Fraser (1983) discussed the use of concept maps in an effort to reveal not only what students understand, but also any potential misconceptions that they may hold in science. They suggested that teachers routinely utilize concept maps as a way to assess their students' science learning because it required relatively little time and effort in the already constrained classroom environment. By doing such, teachers could use concept maps as a type of formative assessment to determine which topics or concepts students did and did not understand thoroughly. Teachers could then use this information to inform their teaching practices, including the amount of class time they spent on a particular topic, or providing targeted support to one or more students who might be struggling.

Chapter 3: Method

While some argue that concept maps should, at most, be used for formative assessment purposes, they can also provide a summary of what has been learned at the end of a learning task or unit of study. Many have used concept maps as a summative assessment of student learning (Moreira, 1985; Nicoll, 2001; Novak & Gowin, 1984; Pendley, Bretz, & Novak, 1994; Shavelson, Lang, & Lewin, 1993; Turns, Atman, & Adams, 2000) and have developed methods for scoring them in an effort to assign grades to students.

Shavelson, Lang, and Lewin (1993) conducted a review of literature on the various methods for concept mapping as well as the techniques for scoring concept maps. They found that there were more than 128 possible variations for constructing concept maps, with almost as much variation in scoring techniques and called for an integrative cognitive theory that would limit this variation and assist in the reliability and validity of concept maps as an assessment. Additionally, they noted the wide variation in methods for scoring concept maps as well. Scoring methods ranged from recommending that they not be scored at all, to a detailed scoring system (described in Novak & Gowin, 1984). Similar to the *criterion map* used by Novak and Gowin (1984) which student maps were compared to, Lomask and colleagues (as cited by Shavelson, Lang, & Lewin, 1993) used an *expert map* that student maps were evaluated against. For concept maps to be used as a true assessment, Shavelson, Lang, and Lewin (1993) believed that there must be "a combination of a task, a response format, and a scoring system. Without all three, the assessment is not completely known" (p. 18).

While Shavelson, Lang, and Lewin (1993) found that concept maps can provide an authentic assessment with reliability and validity, they noted concern about students' ability with concept mapping that may affect their performance, as well as teachers using this type of assessment incorrectly and "teaching to the concept map test" (pp. 28-29). Although the use of concept maps as a summative assessment can provide instructors with a fairly accurate depiction of a student's understanding of overall content covered in their course, it can also be somewhat overwhelming to evaluate a concept map that contains such a large amount of information (for example, see concept map in Turns, Atman, & Adams, 2000). Because this study did not involve eliciting student conceptions for the purpose of informing teaching, the concept maps generated were not used as an assessment. Rather, concept maps were used only to inform the researcher on participants' understandings of concepts and to provide a fuller picture of their overall conceptions of engineering design.

Concept maps alongside interviews. Many have found that using concept maps alone does not give one a *full* picture of a subject's understandings or conceptions (Ruiz-Primo & Shavelson, 1996; Shavelson, Lang, & Lewin, 1993; Turns, Atman, & Adams, 2000; Umoquit, Tso, Burchett, & Dobrow, 2011; Van Zele, Lenaerts, & Wierne, 2004). Novak (1980) argued that "each person has idiosyncratic meanings for each concept, determined in part by the experiences that gave them special propositional meaning" (p. 283) and that this can be exemplified in the construction of concept maps.

Because phenomenography as a theory explains that individuals "experience, conceptualize, perceive, and understand" a phenomenon differently (Marton, 1986, p.

31), concepts maps provide an excellent framework for eliciting, what Novak (1980) called, a student's *cognitive map*. Additionally, many phenomenographers argue that one can gain a better understanding of subjects' experiences, beliefs, and conceptions of the phenomenon under investigation by looking at their generated work (including concept maps) alongside conducting in-depth interviews (Beiers & McRobbie, 1992; Marton, 1986).

In this study, which is grounded in the theory of phenomenography, concept maps were used before interviews to elicit participants' initial understandings about engineering design visually. Next, these concept maps were used during interviews to help participants visualize their thoughts and understandings and to help inform the researcher of areas to probe for understanding or clarification. Concept maps were also used throughout the interview as a reference document that participants could add to as they went along and thought of new concepts or connections that they had not realized before. The ways that concept maps were used in this study, supported by existing research, will be described in more detail below.

Concept mapping before interviewing. It has long been recognized that interviewing is an effective technique for eliciting the conceptions and understandings of individuals. Novak and Govin (1984) discussed the types of knowledge claims that can be made from varying types of interviews depending on the tasks the interviewer sets and the questions asked. In their work, the principle objective of interviews was to ascertain what the learner knew about a particular body of knowledge. They suggested that researchers could ask a sample of students to construct concept maps using the same key concepts and also add additional concepts as they saw fit. From there, any misconceptions or incomplete understandings that students might have had could be prepared for and probed in individual interviews with the entire sample of students.

This method of using participant-generated concept maps to help guide interviews relies on the fact that enough information can be gleaned from those concept maps and that the cognitive structures of the participants will align in a meaningful way. Kinchin, Streatfield, and Hay (2010) discussed using concept maps as a preliminary step before interviewing in qualitative research, and hypothesized about whether interviews focused on respondent-generated concept maps would be more effective for evidence-gathering compared to traditional interviewing techniques. Over the years, multiple researchers have looked at just that and have used interviews alongside concept maps to elicit knowledge and understandings in a variety of contexts (Edwards & Fraser, 1983; Englebrecht, Mintzes, Brown, & Kelso, 2005; Moreira, 1985; Rye & Rubba, 1996, 1998; Van Zele, Lenaerts, & Wierne, 2004; Wheeldon & Faubert, 2009; Zanting, Verloop, & Vermunt, 2003).

In this study, while no concept maps were created to guide the initial interviews of prospective and preservice interviews, their initial concept maps were used to help guide subsequent interviews and the focus group interviews of the practicing teachers and teacher educators. The amount of time and effort to create the initial concept maps—including the instructions given to create concept maps in general—was taken into account by researchers for the later interviews. Some interview questions and probes by researchers during later interviews were modified based on these initial concept mapping activities. Additionally, some concept maps were selected and used as example maps in later interviews of some participants. In these ways, concept maps were used by researchers as a tool before some interviews.

Using concept maps during interviews. Some researchers suggest that concept maps can be used during interviews either with the subjects' participation, or used only by the researcher to guide the interview. If only researchers use the concept maps, typically they are used to plan and guide the interview protocol—including selection of appropriate questions and probes. If subjects use concept maps during interviews, it is typically as a reference tool to guide their thinking and remind them of their thoughts on the topic, and facilitate discussion with the interviewer. In this study, concept maps were used as a guide for interviews—questions were framed around them—and they were used to facilitate discussion and gain deeper understandings of the perceptions and knowledge of participants about engineering design.

Concept maps guiding interviews. Some researchers suggest that interviewers use concept maps to guide interviews because concept maps, especially those that are student-generated, provide the interviewer with insight on what may or may not be known and can help them decide which questions to ask and which areas should be probed further. Edwards and Fraser (1983) noted that interviewing is widely accepted as a method for revealing cognitive structures and that concept maps usually provided an accurate portrayal of students' comprehension of concepts when compared to in-depth interviews. In their study, students constructed concept maps first, and then the interviewer was able to use these maps as a tool to probe for additional information on concepts. This allowed the interviewer to elicit a more complete description of the student's overall comprehension of the topic and further explanations on the concepts and propositions from the concept map.

Novak and Gowin (1984) suggested that one should begin an interview with open-ended questions, preferably about an auxiliary item, such as a picture, model, or even a concept map. From this initial open-ended question, a train of comments and related questions follow. This sequencing of an interview "helps interviewees to collect their thought so that they reveal more about what they know" (p. 128). Their goal with this method of using concept maps as a guide for interviewing is to have the students "reveal as many of the concepts and propositions in his or her existing cognitive structure as is possible" (p. 126). They believed that a well-executed clinical interview, following all of the steps mentioned above, "provides by far the most penetrating assessment of a student's knowledge" (p. 128).

Edwards and Fraser (1983) suggested that teachers conduct on-on-one interviews with their students alongside student-generated concept maps of science topics to gain a fuller perspective of their cognitive structures and understandings. While they admitted that if teachers did this routinely (as they suggested) it would require major restructuring of the classroom and teaching environment, they thought the benefits might greatly outweigh the difficulties. Any one method used to elicit student understandings, such as concept map, when used in isolation will most likely not provide a full picture of those understanding, but when used in conjunction with interviews, teachers can gain a broader view of them.

Concept maps to facilitate discussion. Some researchers have found that concept maps are helpful when used during interviews to facilitate discussion between the interviewer and interviewee. To do this, concept maps can be generated by participants before or during an interview, and then used to help guide interview questions, help the interviewer probe concepts or connections between concepts, help guide the thinking of the interviewee, and provide a framework for overall discussion on the main topic.

Drawing on Novak and Gowin's (1984) work, Rye and Rubba (1996, 1998) explored the use of concept maps as an interview tool to externalize students' understandings. They cited a common issue of traditional interviewing techniques, the difficulty researchers have in eliciting knowledge fully, and claimed that concept maps may help remedy this. They discussed how concept maps, if used in conjunction with interviewing, "may cause students to reflect more so on what they know and say, thereby stimulating spread of activation [of knowledge held in long-term memory], and leading to further recall and elaboration" (Rye & Rubba, 1998, p. 522).

Moreira (1985) suggested that concept maps be used alongside interviews to get a more accurate picture of a student's understandings on a topic. An example of this technique, discussed by Moreira, involved students constructing concept maps that included a set of given key concepts from the teacher (the map could include more concepts as well). The students were later interviewed by the teacher and the concept map was used as a tool to facilitate discussion where they would explain their map, justify the organization of the concepts, and clarify their meanings of relationships between concepts. Students were asked to do this process three times during the period of a physics course, where the final map and interview would ideally represent the entirety of the content learned in the course. In this example, students expanded on their ideas from their concept maps through discussions with their teacher. Meanwhile, the teacher was able to gain a fuller picture of the student's understanding of a topic and how those understandings developed over time.

Rye and Rubba (1996, 1998) studied a group of students who were asked to construct concept maps during an interview to help them answer some of the interview questions and a control group who was interviewed without concept mapping. In the concept mapping group, students tended to respond positively to the concept mapping technique and discussed how it helped them organize their thoughts, facilitated further recall of knowledge, and fostered metacognition. Some inferred that the visual nature of the concept map helped them while thinking about interview questions. These students also discussed the value of concept maps in general, such as using them as study aids or to facilitate thinking. This perceived value of concept mapping was further evidenced by multiple control group students sketching concept maps during their interviews even when they were not asked to.

Some researchers have found value in utilizing both methods of concept mapping and interviewing concurrently, but not necessarily occurring simultaneously. A study on an undergraduate physical geology course utilized the technique of constructing concept maps concurrently with interviews, to help determine the degree to which objectives for student understanding were being met and to document change in students' conceptual knowledge and understandings (Englebrecht, Mintzes, Brown, & Kelso, 2005). They asked students to construct concept maps during five "concept mapping episodes" in evenly spaced intervals throughout the study period (p. 265). In addition, researchers conducted clinical interviews with students once at the beginning of the study, and again at the end. In these interviews, among other tasks and questions, students were given their concept maps and "asked to elaborate on what they diagrammed, their reasoning for the entries, and knowledge they perceived as having gained since the last mapping episode" (p. 266). Students were also asked to make reference to their concept maps throughout the entirety of the interview.

Englebrecht and colleagues (2005) claimed that this technique is more effective than traditional assessment formats that either constrain student responses (e.g., multiple-choice or short answer questions) or may be influenced by factors unrelated to their knowledge of the subject matter (e.g., language or writing ability in essays or reports, or speaking and social ability in presentations or projects). While this particular method for using concept maps and interviews may be effective and conducive in certain setting—like the college course described above—this study utilized both of these methods simultaneously to obtain as full a picture as possible of the conceptions of engineering design from individuals along the learning-to-teach continuum.

Summary. Using concept maps in conjunction with interviews as a tool to investigate student understanding on a topic is a more commonly used method in qualitative research now, however, as discussed earlier, there are many ways this can be done and varying reasons for doing so. The approach most pertinent to my research was originally described by Novak and Gowin (1984) and involved asking participants to create concept maps in isolation before an interview and then probing their ideas and understandings using that concept map during a later interview.

In addition to following this approach in a series of interviews throughout the study, I used selected concept maps as a reference in some interviews with certain participants, and asked targeted questions about them. More specifically, I used example concept maps generated by prospective teachers to help guide the interviews of and gain further insight into the other teacher groups – to learn more about their ideas and understandings of engineering design.

As part of my analysis procedures, described further later in the chapter, I not only examined at the participants' concept maps in isolation, but also compared them to their interview transcripts to get a complete picture of each participant's conceptions and understandings about the topic-at-hand. More detailed descriptions of each step of the data collection process is given in the sections below.

Methods

To answer the above research questions, audio-recorded individual interviews were conducted with prospective and preservice teachers at regular intervals throughout the 2015-2016 academic year. Concept maps were also collected intermittently from prospective and practicing teachers. Focus group interviews were conducted with practicing teachers and teacher educators; each participating teacher or teacher educator was interviewed only once. Rather than create their own concept maps, focus group interviews included discussion of example concept maps. All concept maps and interview questions examined in this study related to engineering design and were used to identify participants' conceptions of engineering design. Demographic information about the prospective and preservice teachers was obtained via survey, separate from the interviews. Each of these will be discussed in more detail in the sections below. See Figure 3a for a timeline of the data collection process.

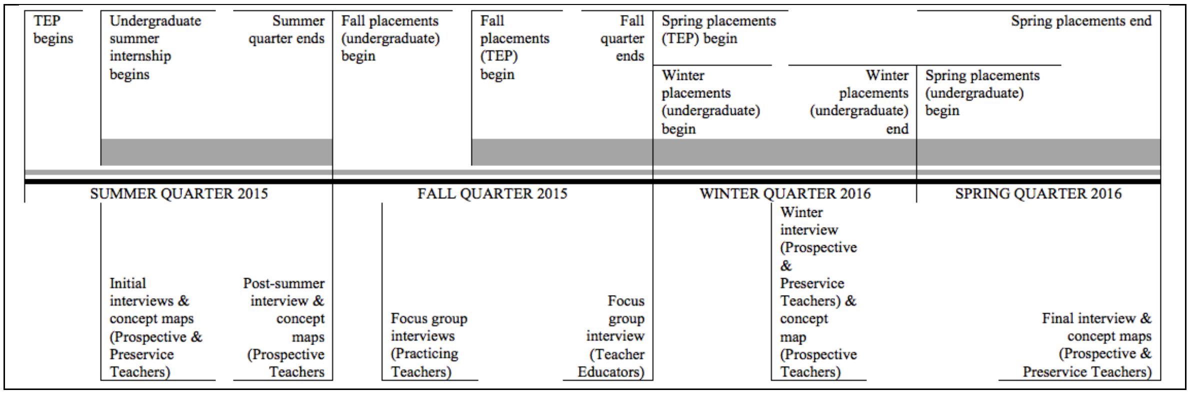
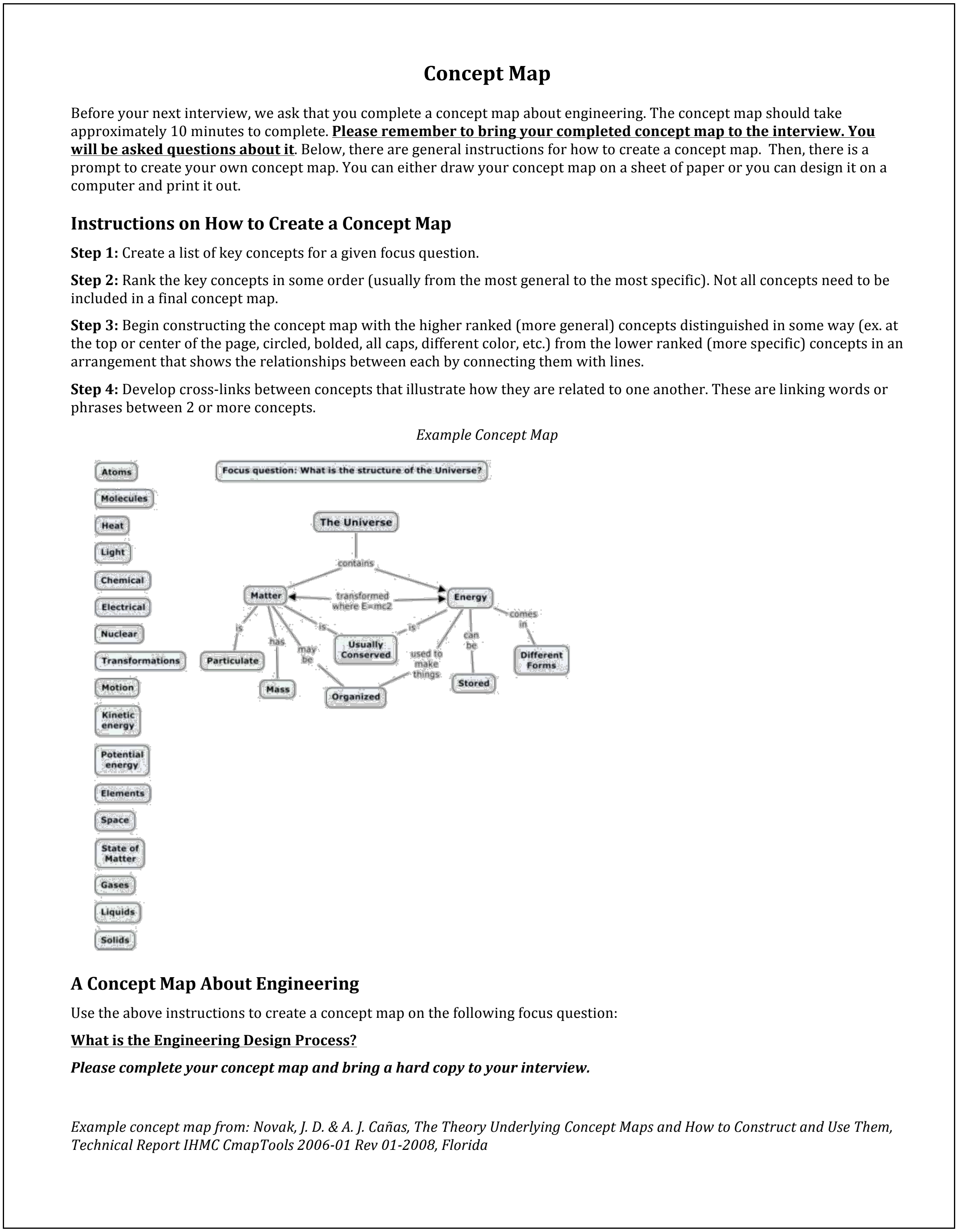


Figure 3a. Timeline of data collection by academic quarter.

Concept maps. Prospective and preservice teachers were periodically asked to create concept maps using the following prompt: What is the engineering design process? Instructions for creating a concept map were based on those provided by Novak and Cañas (2008) and given to all participants before they were asked to create their own (Figure 3a). The provided instructions include four steps: (1) List the key concepts for the focus question. (2) Rank the concepts in some order. (3) Construct the map distinguishing higher ranked concepts from lower ranked ones, while arranging them in a way that shows the relationships between each. (4) Develop links between concepts using lines and linking words or phrases (from Novak & Canas, 2008, p. 21). A sample concept map was also provided.



Concept Map

Before your next interview, we ask that you complete a concept map about engineering. The concept map should take approximately 10 minutes to complete. **Please remember to bring your completed concept map to the interview. You will be asked questions about it**. Below, there are general instructions for how to create a concept map. Then, there is a prompt to create your own concept map. You can either draw your concept map on a sheet of paper or you can design it on a computer and print it out.

Instructions on How to Create a Concept Map

Step 1: Create a list of key concepts for a given focus question.

Step 2: Rank the key concepts in some order (usually from the most general to the most specific). Not all concepts need to be included in a final concept map.

Step 3: Begin constructing the concept map with the higher ranked (more general) concepts distinguished in some way (ex. at the top or center of the page, circled, bolded, all caps, different color, etc.) from the lower ranked (more specific) concepts in an arrangement that shows the relationships between each by connecting them with lines.

Step 4: Develop cross-links between concepts that illustrate how they are related to one another. These are linking words or phrases between 2 or more concepts.

Example Concept Map

A Concept Map About Engineering

Use the above instructions to create a concept map on the following focus question:

What is the Engineering Design Process?

Please complete your concept map and bring a hard copy to your interview.

Example concept map from: Novak, J. D. & A. J. Cañas, The Theory Underlying Concept Maps and How to Construct and Use Them, Technical Report IHMC CmapTools 2006-01 Rev 01-2008, Florida

Figure 3b. Concept map instructions.

Interview process. The interview process for teacher participants varied depending on the schedules of the program or internship they were taking part in, their personal schedules, and the amount of time they were able to spend at any one given interview. Some participants were interviewed individually several times throughout the 2015-2016 year, while others only participated in one focus group interview during the year.

Prospective teachers were interviewed before and after their five-week intensive placement, mid-academic year, and at the end of the academic year. Preservice teachers were interviewed shortly after starting the teacher education program, but before beginning their classroom placements, mid-academic year, and at the end of the academic year. Focus group interviews were conducted with practicing teachers after the five-week intensive internship, during the start of university's the academic year. Finally, focus group interviews were conducted with the teacher educators mid-academic year, after they had taught at least one course to the prospective or preservice teachers.

Prospective teachers were asked to complete concept maps for each interview, while preservice teachers did for some, and the other groups did not construct concept maps at all. Rather, when concept maps were not created, participants were asked to provide feedback on example maps. These interviews and the methods used during them are discussed in more detail below.

Prospective teacher interviews. Prospective teachers created concept maps before each interview they participated in, for a total of four concept maps throughout the 2015-2016 year. One concept map was created before their 5-week summer internship experience, before they had spent any time in the high school field placement or taken part in any seminar sessions. The second concept map was created immediately after this summer experience to capture the potential effect that their summer intensive field experiences and seminar sessions had on their understandings of engineering design. The third concept map was created during the winter quarter, halfway through the university's academic year. The amount of time that the prospective teachers spent in a high school classroom varied throughout the academic year and thus this mid-point concept map represented a wide range of experiences. The fourth and final concept map was created at the end of the 2015-2016 academic year, after their internship experience was completed. It is important to recall that the prospective teachers had no seminar sessions with university teacher educators during the university's academic year, only during the 5-week intensive summer experience.

Preservice teacher interviews. Preservice teachers were asked to create concept maps for their initial interview (before being placed in a classroom) and their final interview at the conclusion of the school year. The same instructions (discussed above and based on Novak & Canas, 2008) were given to preservice teachers. At the time the initial concept map was created, preservice teachers had completed introductory courses on science education, had had limited instruction on engineering education, and had no field placement experiences. Preservice teachers were also asked to create a concept map at the end of the academic year, after completing their coursework and field experiences for the program. During their mid-year interview, preservice teachers were not asked to construct their own concept map, but rather to analyze and give feedback on two example concept maps (discussed more below).

Practicing teacher and teacher educator interviews. Practicing teachers, both those from PBEA and EA, were interviewed once during the 2015-2016 year after they had spent at least one quarter with students. Teacher educators were also interviewed once, midway through the year, after they had taught at least one course to the prospective or preservice teachers. Practicing teacher interviews included two focus group interviews—one with both EA teachers and one with the four PBEA teachers that teach in each of the four content-area spaces—and another individual interview with the PBEA teacher that serves as a coordinator and advisor for the academy. The three teacher educators were interviewed together. All interviews followed the same protocol, which asked about their background related to engineering, their views and knowledge of engineering, and their teaching of engineering design either in the high school academy setting or the university, teacher education setting. They were also asked to analyze and provide feedback on two example concept maps (discussed more below).

Example concept maps. In an effort to reduce the burden placed on participants, example concept maps were used during some of the individual and focus group interviews in certain contexts. The undergraduate, prospective teachers' concept maps were used to create these example concept maps and thus, they were the only participants that did not analyze example concept maps during the study. The rationale for using example concept maps and the process of creating them is detailed below.

Rationale. Researchers determined that it would take too much time and completion could be guaranteed for many of the participants to construct their own concept maps prior to all the interviews. Prospective and preservice teachers were receiving funding as part of their respective scholarship program and thus time and accountability for them could be more or less assured. In contrast, practicing teachers and teacher educators were volunteering to be a part of the study on their own time. In addition, because these were focus group interviews (except with Kristy), if only some of these participants had created a concept map beforehand, a subset of participants would have to wait for the remaining individuals to create maps.

In an effort to alleviate some of these concerns, researchers decided to select example concept maps that could be shown to participants during an interview, that could help guide the interview questions, and that could elicit some of the participants' general thoughts and understandings of engineering design. These example concept maps were selected from the concept maps created by the undergraduate prospective teachers after their 5-week intensive summer experience. These concept maps were used because they represented the conceptions that novices in high school science and engineering teaching may hold with minimal instruction and experience. When the other teacher groups, who were further along in the learning-to-teach continuum, were shown these concept maps, they were told these example concept maps were being shown to them to solicit their expert opinion.

Selection. The process of selecting two example concept maps to be used for the duration of the study involved examining all of the prospective teachers' post-5-week summer experience concept maps and selecting two that demonstrated key components of engineering design, discussed in Chapter 2 above. The first concept map (Figure 3c) selected was from a participant who was placed at the Eco Academy and did not have any direct classroom experiences in engineering. This map demonstrated a more basic engineering design process that focused on product design and testing. This process more closely resembled the type of engineering design that is done in professional engineering. Another important component of engineering design that this first example concept map included was an emphasis on a final product and a definitive end to the process.

The second example concept map was selected because it was more complex and involved more concepts and statements and more connections between them. This map demonstrated key components of engineering design that the other map did not, including brainstorming multiple ideas, researching, and creating goals or criteria for success for the product or solution. This second example concept map, most importantly, did not demonstrate that there is a final product or solution that should result in going through the engineering design process. In fact, this map asked, “How could it be better?” after a solution has been deemed successful by the engineer.

Construction and use. To ensure the anonymity of the prospective teachers who created the two example concept maps, I redrew both maps, while still maintaining the fidelity of the concept maps’ concepts, links, and overall structure. When other teacher groups were shown these example concept maps, they were informed that they had been redrawn, so there was no attempt made to try and determine which prospective teacher drew them. They were, however, informed about which school placement the prospective teachers who drew the maps had been placed in, but only if they explicitly asked for this information during the interview; this usually did not occur.

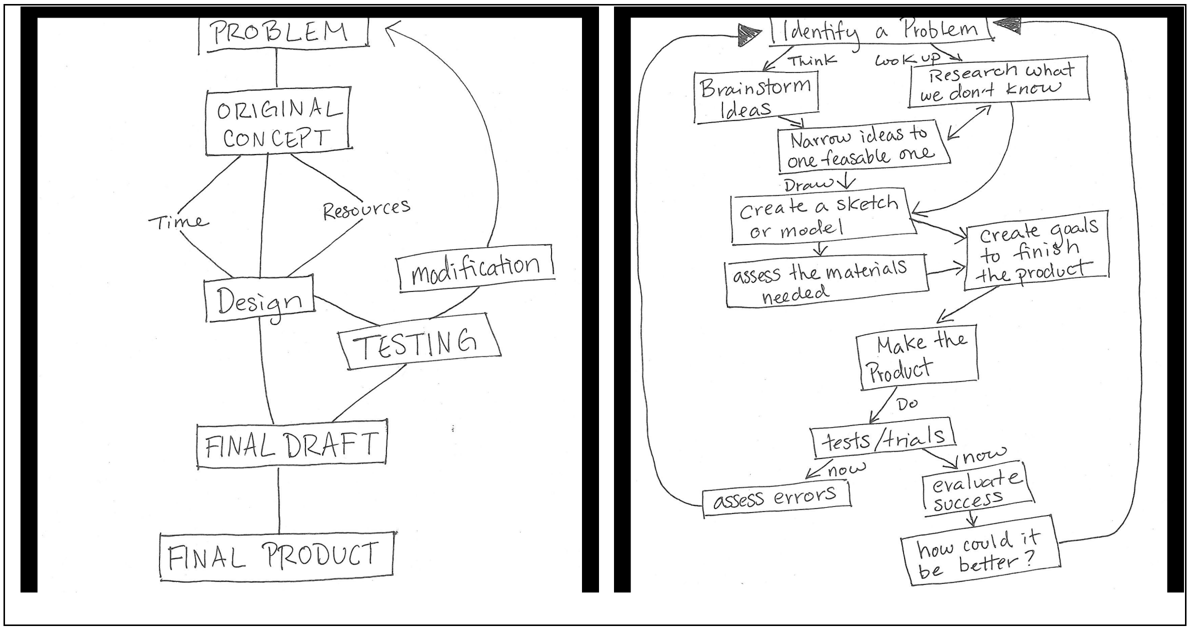


Figure 3c. Example concept maps.

Additional information about the interview process. Interviews were conducted using a semi-structured interview protocol, so that the questions were consistent across teachers, but flexible enough to adapt to each teacher as the interview progressed (Brenner, 2006). As part of each interview, all participants were asked about their previous experience with engineering (formal and informal experiences, connections to engineers, etc.) to gain a baseline level of their potential understandings. All participants were also asked to define what they thought engineering was, how “doing” engineering was similar to or different from “doing” science, and how engineering education was similar to or different from engineering in the field. Prospective and preservice teachers were also asked if they considered themselves, and the students and teachers they worked with, engineers. Throughout the year, they were asked these questions again and further asked what experiences might have changed their understandings. Lastly, all participants were asked about how they either did teach, or might teach engineering and the design process to high school students (or preservice teachers, in the case of the teacher educators).

As this study was part of a larger research project, other questions besides those related to engineering were included in the interviews. For our purposes here, however, only those parts of the interviews related to engineering were examined. Interviews ranged from approximately 15 to 60 minutes in length. Interviews were conducted by six members of the research team and were digitally recorded.

Concept map use during interviews. Because many researchers have found that using concept maps alone does not give one a *full* picture of the subject's understandings or conceptions (Ruiz-Primo & Shavelson, 1996; Shavelson, Lang, & Lewin, 1993; Turns, Atman, & Adams, 2000; Umoquit, Tso, Burchett, & Dobrow, 2011; Van Zele, Lenaerts, & Wierne, 2004), prospective and preservice teachers were asked questions related to their concept maps during interviews. All interviews with prospective teachers involved looking at the concept map they had created immediately prior to the interview and answering a series of questions related to it. Preservice teachers went through this same interview process in their initial interview at the beginning of the 2015-2016 year and again at the end of the year during their final interview.

In both prospective and preservice teachers' initial interviews, they were asked to draw concept maps with the guiding question: What is the engineering design process?

They were asked to bring this concept map to the interview and asked the following questions about those concept maps as part of the larger interview protocol:

- Can you briefly describe your concept map?
- Can you elaborate on **one** part of your concept map that you think is the most important? Why?
- Which **one** part of your concept map do you think you need more help to understand? Why?

In subsequent interviews about their concept maps, additional questions were asked about where the information from those maps had been obtained. For example, if there was a component of engineering design that was added to their concept map, the researcher asked whether that information was obtained from their experiences in the classroom, from courses or seminar sessions, or from another source. In addition, prospective and preservice teachers were asked about which parts of their concept map on engineering design were the most important for *teaching* engineering and for *doing* engineering. They were also asked which part of their map they might need more help to understand (either for teaching or doing engineering).

During the preservice teachers' mid-year interview, they were shown the two example concept maps created by the prospective teachers described above (Figure 3c). They were then asked a series of questions related to these. The concept maps were shown one at a time to the preservice teachers with the following excerpt from the interview protocol:

> We asked undergraduate interns to draw concept maps of what they thought the engineering design process was. We wanted your opinion on a couple of these concept maps. [Show one map. Ask the questions below. Then show the next.]
>
> - Do you think this individual has a good understanding of the engineering design process?
> - Is there anything you think he or she may be missing or misunderstanding?
> - How does this intern’s view of engineering design compare to yours?

The practicing teachers and teacher educators were also shown these two example concept maps during their focus group interviews and were asked the same questions about them. The only difference between the interview protocol for these two teacher groups and the preservice teachers was the addition of “expert” in the introduction to the task: We wanted your *expert* opinion on a couple of these concept maps. In these focus group interviews, each participating practicing teacher or teacher educator was given individual copies of each concept map to reference. This was done to ensure that each participant had an equal opportunity to examine the example maps closely and gather their thoughts independently before responding to the questions in the focus group setting.

Summary. A series of concept maps were collected from prospective and preservice teachers. Interviews were also regularly conducted with these two teacher groups throughout their time in an undergraduate internship (prospective teachers) or teacher education program (preservice teachers) during the 2015-2016 academic year.

During the interviews, participants were asked to discuss the concept maps that they had created immediately before those interviews.

In one interview with the preservice teachers and the focus group interviews with practicing teachers and teacher educators, example concept maps were used in place of having them create their own. These two example concept maps were drawn by prospective teacher participants and exemplified various key components of engineering design. Participants who were shown these example concept maps were asked to examine them and provide insight and opinions on them. They were also asked to compare these example maps to their own views of engineering design.

All concept maps were collected from participants and all interviews were audio-recorded and downloaded into digital audio files. All data was assigned pseudonyms and were kept together depending on when the concept map or interview took place to ensure that researchers could cross-reference concept maps with the corresponding interview that discussed it. By doing this, analysis procedures could begin without additional organizing or possible loss of data or associated information. The next step in the study, analyses, is discussed in detail in the next section.

Analysis

Analyses for this study were conducted following a phenomenographic approach (Marton, 1981) in an effort to answer the following questions: (1) What conceptions of engineering design did teachers along the learning-to-teach continuum hold? (2) What characteristics or experiences of participants appeared to influence their understanding of engineering design, such as their engineering experience, other STEM experiences, or personal background? In the following sections, I describe each of the three levels of analysis used in this study, as well as provide a brief background on the methodology of phenomenography.

Methodology

Phenomenography is a well-documented research approach that goes back to the 1970's and has a specific series of steps to elicit the desired information (Marton, 1981). Because phenomenography rests on the notion that "each phenomenon, concept, or principle can be understood in a limited number of qualitatively different ways," the researcher must uncover and map any differences into conceptual categories (Marton, 1986, p. 31). To do this, researchers analyze the products of people's work (such as drawings, writing, etc.) and transcripts from interviews. These data are differentiated based on reference to different phenomena or parts of a phenomenon, and then sorted into conceptual categories that are organized based on fundamental characteristics developed for each (Svensson, 1997). When established criteria for inclusion and critical dimensions of variation are created for all categories, a system of meaning, or "outcome space," is created (Daly, Adams, & Bodner, 2012; Hasselgren & Beach, 1997; Marton, 1986; Marton & Pong, 2005).

Hasselgren and Beach (1997) described five variations of phenomenography in their paper on the methodology: experimental, discursive, naturalistic, hermeneutic, and phenomenological. Experimental phenomenographic research, which occurred early on in its adoption as a methodology, was a content-oriented study of learning where researchers tried to map preconceived ideas about specific phenomena and sought to find out if these were modified through instruction. I utilized this approach through my data analyses by first using the basic phenomenographic approach to construct conceptual categories and later used the information on the participants to determine if these experiences (analogous to instruction on the topic) had influenced their conceptions. Each of the three levels of analysis used is discussed in detail below.

Preparing for Analyses

The analytic process began by transcribing those parts of teachers' interviews pertaining to engineering and digitally scanning all prospective and preservice teachers' concept maps. Once all of the data had been transcribed and digitized, it was organized by participant, group (prospective teachers, preservice teachers, practicing teachers, and teacher educators), and time during the 2015-2016 year. From there, analyses using a primarily phenomenographic approach began.

While organizing the data, any missing information was documented. For the prospective teacher group, Ralph was missing an interview transcript for the post-5-week summer interview (he was interviewed, but the audio recorder malfunctioned so the data was lost). For the preservice teacher group, Molly was not asked about her experience with engineering, so that aspect of her background could not be documented or included in analyses. The practicing teachers at the Eco Academy were not explicitly asked about whether they knew any engineers, and thus, that specific aspect of their experience with engineering could not be documented or included in analyses.

Table 3e

Participants' Experience with Formal and Informal Engineering

		Formal Engineering			**Informal Engineering**			
Teacher Group	**Name**	Eng. Course	Eng. Research	Professional Eng. Job	Non-Eng. Courses	Eng. Outreach	Doing Informal Engineering	**Familiarity with Engineer(s)**
Prospective	Zeb		X		X			X
	Xandra	X				X	X	X
	Saul							X
	Rick						X	X
	Ralph	X			X			X
	Nick	X						X
	Monty				X			X
	Carlos				X		X	X
	Anthony						X	X
Preservice	Molly*							
	Kari							
	Adam	X			X			
	Caitlyn	X			X			
	Sasha	X						X
	Kayla	X			X			
	Haylee				X			
	David				X			
Practicing	Ken				X			X
	Kurt	X	X			X		X
	Dana				X		X	X
	Josh			X				X
	Kristy				X		X	X
	Macy	X			X		X	
	Sandra		X	X				
Educators	Sally				X			X
	Patty	X			X		X	
	Jasmine					X		X

*Background information on engineering experiences was not asked about during initial interview

In addition, the initial interviews or focus groups for all participants were listened to and information on each participant's prior experience with engineering was gathered (Table 3e). Prior experience with engineering included both formal and informal contexts. Formal engineering included engineering courses, research, or professional engineering experience. Informal engineering experience included non-engineering courses that incorporated some aspect of engineering, engineering outreach, or doing informal engineering (e.g., building things, “making”, problem solving, etc.). Participants were also asked about their familiarity with engineers—close family, extended family, co-workers, friends, and others This information was necessary for level 3 analyses, described in more detail below.

Level 1 Analysis

The first level of analysis consisted of sifting through all of the data (including concept maps and interview transcripts) to establish all of the various aspects of engineering design that participants identified -- finding the “imaginative variation” in the data (Marton, 1986, p. 41). This part of the analytic process is important because it allows the researcher to clearly see the wide variation of possible conceptions that participants hold about the particular topic of study—engineering design. As part of these initial analyses, the framework for engineering design—created in Chapter 2—was used to help guide me in selecting the multiple aspects of engineering design discussed by participants and provided an organizational structure to aid in later analyses. While this already-established framework held many of the aspects of engineering design that were discussed by participants, some were not easily mapped to the framework, and therefore, six new aspects were created: Engineering Is Integrated, Inspiration, Physical Object, Thinking Like an Engineer, Using Mathematics, and Using Technology (see updated Aspect of Engineering Design Framework below; Table 3f).

To conduct level 1 analyses, concept maps and interview transcripts were marked and segmented according to relevant aspects of engineering design that they addressed. The unit of analysis was formed when there was sufficient evidence that a particular overall meaning had been expressed. For example, a transcript was segmented into "identifying constraints" only when the participant had talked about things an engineer should take into consideration when designing (e.g., time, money, criteria, etc.), and not if they discussed identifying or solving an engineering problem in general.

Table 3f

Aspects of Engineering Design Identified in Literature and During Analyses

NGSS Component	Identified Aspect
1. Defining and delimiting engineering problems	**Problem or need** The first step in the engineering design process is to identify the engineering problem, which is usually a human "need" or "want". In addition, it is necessary to identify the "true need" to be addressed by elaborating on the initial problem or need and determining what truly needed `(which may differ from what was initially thought was needed).
	Thinking about the user An engineering designer must think about the person or people (the user(s)) that could potentially use the solution they are designing. To do this is to "empathize" with the user. This can include researching the marketplace or conducting user studies.
	Research Researching what is already out there is critical for engineering design. This includes researching existing solutions, models, or processes that can make the design process easier or obsolete all together. In addition, researching the possible tools, technology, and information related to the problem at hand can be beneficial for the engineer and the design. This is part of component one because you are researching the problem and/or constraints before engaging in any design.
	Identifying constraints Identifying and developing the criteria or constraints for the engineering problem. These are things that the engineer must keep in mind throughout the design process, and that must be taken into consideration into the design. Business constraints are those that are more important from an economic perspective—including financial feasibility, time, legal consideration, and analyses of economic factors. There are a number of other possible constraints, including (but not limited to) the natural laws (e.g. the laws of physics, etc.), human considerations and use (e.g. ergonomics), and many more.

	The scope of design It is important for engineers to limit the scope of the problem that they are working on for efficiency's sake. This includes realizing that if a solution to the problem at hand falls too far outside this scope that it may not be an ideal solution.
	Subproblems As engineering problems become more complex, it is necessary for engineers to break these larger problems, processes, or designs into smaller subparts. In this way, they can work on one subpart at a time and bring them all together to solve the larger problem.
2. Designing solutions to engineering problems	**Communication** Designs that attempt to solve an engineering problem must be communicated to others. To do this, designs can be communicated using multiple modes—verbally, visually, mathematically, through writing, or some other form. Examples of designs that are communicated include written or spoken descriptions, drawings, prototypes or models, computer aided designs (CAD), mathematical models or equations, etc.
	Developing solutions A major component of the engineering design process is the development of solutions that attempt to solve the engineering problem. It is considered best if an engineer develops multiple possible solutions, since not all of them will work or fit within the constraints. If there are multiple possibilities, you can choose which one is the best.
	Research Researching what is already out there is critical for engineering design not only at the beginning of the process, but also throughout it. This includes researching existing solutions, models, or processes that can make the design better or the process more efficient. In addition, researching the possible tools, technology, and information related to the problem at hand can be beneficial for the engineer and the design. In particular, it is thought that knowing and using the most advanced resources (science, technology, methods, etc.) creates the best possible design solutions.
3. Optimizing the design solution	**Comparing solutions** After designs have been developed as potential solutions to the engineering problem, it is necessary that they be compared and evaluated. As part of comparing the solutions you must not only look at them overall, but also look at how they meet the identified needs and constraints and the potential value (economic and otherwise) of each.
	Secondary effects Engineers must keep in mind what happens as a result of creating and using the design solution. This includes effects of producing the solution as well as effects of using it, and what will happen once it is retired and no longer needed.
	Design process Once a design has been chosen, it is the engineers job to move it from an abstract form (a basic idea, description, or drawing) and develop it into a more concrete form (a physical prototype or finished product). In addition, the design process must be iterative, where the engineer makes systematic changes to their design and test and redesign as necessary. These process help optimize a solution by facilitating systematic testing and redesigning of the design.

	Testing and evaluating Once a design has been chosen, the engineer must determine how well that solution will actually work. First, it must be determined if it is worthwhile (economically or otherwise) to begin the process of testing and evaluating the design solution to ensure that is meets the identified needs and constraints (specifications). If it is, then systematic testing must take place where the design is evaluated based on its ability to meet the specifications. Based on how well the design does throughout testing, an engineer can have confidence in their decision on the success or failure of that solution. The feedback from these tests also allows the engineer to redesign and improve their design to better solve the problem. **Optimal design** Once an engineering has gone about the process of testing and evaluating their design, they must use the information obtained to come to an optimal design solution. This design will be the best possible version of their chosen solution and should meet the identified needs and constraints as best as possible.
Added aspects from literature— *Mapped to NGSS components*	*NGSS Component 1:* **Competition** Competition can be used to motivate designers to develop better solutions to engineering problems than their competitors. The sense of urgency and awareness of what others are or may be doing to solve the same or similar engineering problem is a critical part of understanding the scope of the engineering problem and what it will take to solve it (the constraints). If an engineer is aware that their direct competition is solving the same problem, a constraint placed on them will then be 'to create a better solution than them'. This helps drive progress and has the potential to lead to the development of better, more innovation engineering solutions. *NGSS Component 2:* **Prior knowledge and experience** Engineers should draw on their own prior knowledge and experiences of similar situations when developing solutions for a given engineering problem. Doing this provides greater context to the engineer, helps them to make more grounded decisions related to potential solutions, and helps them develop appropriate solutions in an efficient manner. *NGSS Component 2:* **Based on science** Engineering is the application of science, involves the use of science or aspects of science, or works hand-in-hand with science. *NGSS Component 2:* **Creativity** Design, in general, is a creative endeavor, and therefore, engineering design must also be creative. Because the goal of engineering design is to develop innovative solutions that solve a problem or need, an element of creativity must remain in the engineering design process to allow the designer to develop those solutions. This may result in a process that is less rigid and systematic since the creative designer needs more leeway to explore creative opportunities and ideas. *NGSS Component 2:* **Aesthetics** The aesthetics of a designed solution goes beyond simply thinking about the way it looks. Rather, aesthetics consists of the overall experience that a user has with the product or process, which engineers must keep into consideration when creating designs.

	NGSS Component 2: **Simplicity** An engineer needs to be efficient in their design process as well as create efficient designs and solutions. To ensure the efficiency of a design, it is usually assumed that simpler is better. If a problem can be solved using a simpler design, then that usually takes less time to create and produce; reducing waste.
	NGSS Component 3: **Collaboration** An important part of effective engineering design is collaborating with others to gain capitalize on their expertise. This is also important because it lessens the work load on any one individual and provides valuable insights and feedback that one engineer may not have thought about in isolation.
	NGSS Component 3: **Evolutionary design** The intuitive problem solving process that human naturally engage in for informal engineering design is centered around 'trial and error' and is usually a longer and less efficient process than formal engineering design. This kind of problem solving process is referred to as evolutionary design because small changes occur over long periods of time as the solution changes and 'adapts' to solve the problem.
	NGSS Component 3: **Final product** The final part of the engineering design process involves creating a final product or process that is the ideal and optimal solution to the identified engineering problem or need. This is no longer a design, but something that can and does go into production, which the engineering no longer has control of. The final product is usually an indication to the engineer of the end to the engineering project, which they will most likely never return to.
	NGSS Component 3: **Never ending process** The engineering design process is never ending because new problems are constantly arising and designs can always be improved, especially as feedback and further research is conducted. Sometimes this cycle is quite short and resembles the iterative redesign cycle discussed in the final component of NGSS above (Optimizing the design solution) or a larger feedback loop that is provided after the final product has been used for some time and new technology reaches and marketplace. With this view of engineering design, an engineer's work is never done.
Aspects added during coding*	*Using technology:* Discussing using industrial or other technologies in engineering/design (e.g. welding, machining, computer programming, etc.)
	Physical object: Engineering creates a physical thing that the engineer designed and created and which can be used by the desired consumer/user
	Inspiration: Engineering can begin with inspiration or an idea for something that may solve a problem, even if you don't realize that it necessarily solves a problem initially
	Using mathematics: Engineering uses mathematics throughout the design process
	Engineering is integrated: Engineering and design are integrated into and applicable for multiple fields
	Thinking like an engineer: Involves critical thinking and problem solving skills

*These aspects are too broad to be mapped to a specific NGSS component of engineering design.

Aspects of engineering design. These analyses yielded a list of all the aspects of engineering design discussed by participants in the data (Table 3g). It was not organized in any meaningful way, and external factors, like my ideas and beliefs about engineering design (with the exception of the already-established framework for engineering design), were not taken into account at this level. By ignoring any preconceived ideas about the structure of engineering design, I was open to any and all possible conceptions that arose naturally in the data. The idea of not making a priori "brackets" within which the data fits is discussed as a fundamental characteristic of phenomenography (Marton, 1981; 1986).

Table 3g

Framework for Engineering Design with Participant Examples

NGSS Component	Identified Aspect	Participant Example
1. Defining and delimiting engineering problems	Problem or need	"So we had to go on our own and identify the problem; we had to think to ourselves, do we actually want to physically stop the door from opening or do we want to just make it make a loud noise so that we're alerted?" (Carlos Interview 2)
		"Identifying a problem … it's the first step. It's the first like, 'Why are you going to do this?' It makes it so much easier if you identify exactly what it is that you want to fix. Especially if it's something that you've already done before, and you're trying to figure out how to make it better. Identifying exactly what it is that you want to do, that you want to work towards is probably the most important part." (Monty Interview 2)
	Thinking about the user	"Accessibility is like, umm, who or what will be using it, and what's the target audience?... It's definitely important in doing engineering, because if nobody can use it then it's kind of useless." (Ralph Interview 1)
		"I remember there was one day that [the teacher] was talking about not only do you have to make something and make it useful for people for it to even be relevant, but you also have to make it… aesthetically appealing. You have to make it to where people are actually going to be inclined to use it… I had never really thought about it in terms of that, that you not only… have to make something that is new and improved, but you also have to make sure that people are going to want to use it". (Monty Interview 3)

		"I think the end goal of engineering is to make a final product that can be used and that is safe and that is functional for everyday life". (Kari Interview 1)
	Research	"My concept map starts with identifying a problem identifying a problem then the next step is researching related aspects of that problem." (Carlos Interview 2)
		"And the process of engineering is thinking through, 'Okay. How do I solve this problem?', and then, you know, like, 'What do I know?', 'What don't I know?', 'What do I have to look into?'. And then taking the information you look into and building upon that." (Monty Interview 2)
	Identifying constraints	"[The] engineering design process… considers various things like cost, fundamental knowledge, and usability, the cost of an item—like maybe an app or a car or any program that depends on its production value. Like if it's very cheap it's probably not going to cost very much because they didn't take many hours to make if it sucks, you didn't spend enough hours on it to improve it." (Xandra Interview 1)
	The scope of design	"I would say an engineering lesson would be give the students as much as you can and a lot of the materials they won't need. So they have to think critically, 'Can I actually use this? Is this relevant at all?'" (Carlos Interview 2)
		"You have to know where to start and you have to be able to constrain what you're trying to solve… I am trying to do X. This is my objective. It has bounds, and I am going to work within those bounds until I solve it. If you misidentify the problem, that can be trouble, but trying to do too many things at once can also be a problem." (Zeb Interview 4)
	Subproblems	"You build a solution and eventually you'll come up with a new problem. And like going from each of these steps to the next, you're going to come up with more issues that you need to solve; another problem comes up from each step. And it's recursive, and iterative. So even once you've solved the first problem, perhaps you have a new problem that's been created from what you've done here. Or you think that you can solve it better in a different way. Or you just have a new problem entirely." (Anthony Interview 3)
		INTERVIEWER: "And then that's like very step. The second step is to visualize a checklist of what that thing should do or should have or require. And then after you have that list you should break down each item on the list, and then work on each item by itself or separate, so it doesn't look like an overwhelming project." SAUL: "Yeah, so you can work on each item one by one." (Saul Interview 3)
Added aspect of engineering design	Competition	"Is it better than anything else that there is already out there, or why is it, why would this be used over anything else?" (Ralph Interview 1)

		"I guess it's just to prevent you from making mediocre product because it's not the best and someone can always come in and make the best. But, if you have the best already, what's the competition?" (Saul Interview 1) "Engineering in the field is kind of… it's capitalism, it's kind of… it's ruthless, and you can get eaten by another company who's making something better and cheaper than you are. And it's more cut throat, it's hardcore. You know, you've got to keep up. If you want to work at Google you've got to prove yourself." (Zeb Interview 2)
2. Designing solutions to engineering problems	Communication	"A design starts with an idea… you have a first draft. You might use computers or CAD to visualize in 3 dimensions what you're thinking of. You should include technical details—how big things are, how much they weigh, what you're going to make them out of, material wise." (Zeb Interview 1) "If you come up with this idea, this new thing, but you can't tell anyone how to build on it, or… no one else knows how to do it, then it's not very sustainable… Anyone who wants to do that has to go through the whole process themselves, which is like backtracking a little bit… What can you now do with it, like how does it help other people?" (Monty Interview 3) "[The] engineering notebook… help[s] them communicate what they're doing, even to themselves. Because I noticed that when I would write about anything, all of the sudden—I start talking about it or start writing about it—I all the sudden understand it differently or I realized I didn't have an understanding of it at all… Being able to communicate this and convince someone that this product or this design is significant or important or necessary." (Xandra Interview 4)
	Developing solutions	"Students make sure that they were coming up with multiple ideas and then looking at all these ideas that they had—either written down or drawn out and whatever—and saying, "This is the best one. This is the one I'm going to go with". And then, you know, part of that is also like, "Okay. Well, these are my backup plans. If this one actually is impossible, if I don't have the means to do it, if someone also doesn't agree with my idea, whatever." (Monty Interview 2) "I think engineering is looking at multiple ways to get to a solution". (Molly Interview 2)
	Research	"Brainstorming ideas of how to solve the problem based on the research that's been done." (Carlos Interview 2) "We had to do all of the research, like who has made this before, what worked, what didn't, and then it was like a lot about green chemistry and like how you can make it without any kind of waste, or all that kind of stuff… We had to look up the research of what had and had not worked and then figure out a way to make it work based on that." (Monty Interview 3)

Added aspects of engineering design	Prior knowledge and experience	“I think engineering is coming up with an idea and creating it out of, you know, like knowledge you've had before or resources you've had before.” (Monty Interview 1)
		“I think engineering is coming up with new ideas and new like creations. Engineering leads to something that hasn’t been done before, and with the process of it, you use any knowledge that you previously have to create something new.” (Monty Interview 3)
		“I think applying what you know to get a solution rather than just like throwing stuff together is going to be more powerful. And that’s what an engineer is doing.” (Caitlyn Interview 2)
	Based on science	“I think that the best way to explain it is that you use science to do engineering. So… they kind of go hand-in-hand because you have to do science to do engineering.” (Monty Interview 2)
		“I guess inventing something that is practical and applying knowledge that’s been found by science.” (Rick Interview 2)
		“I think engineering is solving society's problems using science, hmm, scientific you know, I guess you could say breakthroughs, but using science and being able to apply that to society.” (Xandra Interview 2)
	Creativity	“Anyone can just follow a recipe and build something based on [what] someone tells them to do, but it takes training I suppose to know your problem and then think on your own of new innovative, creative ways to solve the [problem]” (Carlos Interview 1)
		“I think it’d be better to have a brain like an English person than an engineer— [English people] are so much more open and creative. And I feel like [engineering] isn’t creative. And if it is creative, it’s creative in a way that’s enclosed in a box. If I see wood- if I saw a woodpile, it’d be like oh, I build a chair or something. Of course, that’s creative, but someone really creative might think, oh I can, I don’t know, I can make this into art… I think [engineering] is limiting.” (Rick Interview 2)
	Aesthetics	“[The students thought], ‘Why do we have to learn about art? Why do we have to learn about aesthetics?’ Like, ‘why does it matter whether or not our project is pretty? Can we just make it already?’ …. And so I think that some of them got pretty impatient with coming up with all these things on paper that they had to do before they could actually start creating things. But they are really important.” (Monty Interview 2)
	Simplicity	“I think engineers in the field try to be way more efficient, like their goal is efficiency… [a writer] said, ‘no picture has a useless line, and no tool of the engineer, or my bad; no creation of an engineer has a useless part.’” (Rick Interview 2)
		“You don’t have to investigate all the possibilities, once you know a way that works well you can just do that until you run into a problem with it.” (Zeb Interview 3)

3. Optimizing the design solution	Comparing solutions	"If, you know, you come up with a super-good idea but you don't have the means to, you know, construct that, then you can't do it. So it's not a feasible idea." (Monty Interview 2) "[Give students] multiple solutions… I can give a lot more of the specific information about each solution, so that they can compare them and ask 'Why is this one more expensive?' Or 'Why does this one take more time?' versus sitting there and just saying 'This one's better for one reason.' Or 'This one's worse for one reason.' It would be a much better engineering practice if they had to look at so many different ideas at once, and be like 'All right, I like this one over all the others, even though it's not better in every way.'" (David Interview 3)
	Secondary effects	"Like a computer scientist can be like 'Oh, I keep having this problem'. But they might not realize that users will be having a different problem until after they get user feedback." (Xandra Interview 1) "You might be like… 'I didn't realize that this one thing about the environment would affect my - that would affect like my turbine blades, this way'." (Xandra Interview 3) "There's this ethics class… I'm taking right now and it's teaching us about… what to take into account when you're designing. So, you have to take into account everybody who could be affected by it. And the actual repercussions of certain designs, even if the design is made for good reasons it could turn out bad." (Ralph Interview 3)
	Design process	"Then moves on to the next step which is testing that prototype. Based on that test, you collect and analyze data, which is the next step. That collecting and analyzing data either leads to a final solution, if it works perfectly. But most of the time I feel that it then leads to more research about some problem or inconsistency you found from the prototype and the data you've collected; that you research about that. Then go back to brainstorming, and it keeps (chuckle) entering the process; you run that circle until eventually it works and you end up with your final solution." (Carlos Interview 2)
	Testing and evaluating	"My dad works at this company, they make parts of all sorts of things, like space-x, and medical companies and Boeing and other things like that. So he just checks the parts to see if they're in specification." (Anthony interview 1) "If you go, and you just construct a solution, and then call it done, it might work, but there's a good chance that then it just fails. You have to go, and test it, and make sure that what you've done is actually a viable solution and then analyze the data that you collect… That's kind of where you know if you got the right answer or not, is in the testing and then the analyzing data." (Carlos Interview 2)
	Optimal design	"You can go through multiple iterations… just have them do it multiple times until those iterations, getting better and better." (Xandra Interview 2)

Added aspects of engineering design	Collaboration	"[Engineering] also requires collaboration. And that goes back to like getting fundamental knowledge from various fields. But the collaboration happens between visual artists, marketing experts. These are the kinds of things that consumers are looking for… And then the scientists help to refine things, and then the engineers- Aw I didn't include mathematicians, but I mean, they get in the mix." (Xandra Interview 1)
		"The most important [is] maybe 'solicit feedback from other people who also know what they're doing in your area'. Because a lot of times you just kind of tunnel vision through a problem and you don't… It's good to have fresh eyes looking at something that you've come up with to look for problems that you wouldn't anticipate. Because other people are going to think about the problem differently than you and they're going to foresee different complications. And so that's probably the most important, is to either—once you already have a prototype, or if you just have a design or a schematic—to go to someone and say, 'What do you think of this?' Even if it works, someone's probably going to have an idea of how it could work better that you didn't think of, or more efficiently." (Zeb Interview 3)
	Evolutionary design	"Taking previous designs and mindlessly optimizing them or something." (Anthony Interview 2)
		"I think engineering is about making things work better than they do... It's about kind of familiarizing yourself with what's out there, what's been done. You know, don't reinvent the wheel, or whatever… And then we're looking at something and saying, 'Whoever made this is an idiot and I could do it better.' And then you try… It's about improvement. In that way it's kind of iterative, and it's cumulative... So you kind of have to build on what's come before and take small steps. And then that's true overall in general with humanity, but also just you working on a project. You know, make a second prototype, and make it better, and then see what you can improve about that. And then, you know, and so on." (Zeb Interview 2)
	Final product	"The ideal solution. If you had a problem what would be the perfect solution that there would never have to be another solution again because your solution is perfect? Then you try to execute that perfect solution if possible, which it should be possible." (Saul Interview 2)
		"You can always reinvent the wheel, so to speak. However… you probably have to make a product and send it to market or like have a solution to stop the river from overflowing. So there has to be some sort of final product and some aspect of finality." (Adam Interview 2)

	Never ending process	"And then you go through the whole process again based on how you want to make it better or what you want to do next. [INTERVIEWER: Are you ever finished, or does it just keep going?] … You know, once something is satisfying enough, then that's cool. But yeah, I don't think that you could ever get to a point where something couldn't be better." (Monty Interview 2) "Then, you'd have to back around… you continually go through it. [Interviewer: Is there an end to it?] I would say that no. For the most part, there isn't because you can always make something better. It's like, for example, computers. They built a computer like '50s or '60s. And if they stopped there, then… I'd say there's no end just because once you finalize it, you can always optimize it. So, you can always go back." (Ralph Interview 3)
Added aspects of engineering design *Not mapped to NGSS components*	Using technology	"They have this machine called a CMM which coordinate measure machine, and it's like this whole big thing with um these like uh sapphire measuring tips so that it so it wouldn't get worn down and can be programed where to measure each of the things. It reads at different points in whatever the part you're checking." (Anthony interview 1)
	Physical object	"[Engineering is] Solving a problem with something physical" (Saul Interview 1) "No matter how complicated it is, [engineering is] just using the physical world around you to just… to create solutions… engineering is literally like, 'I know this is going to go up if I do this. I know that I can solve this solution by just pulling on… like wrapping this rope around it rather than just pulling on it. Or wrapping this rope around a pulley rather than just pulling on it.' Yeah. There's a little bit more of a physical kind of way about things that engineers have… Physical understanding." (Nick Interview 2)
	Inspiration	"I would just say like, you know, 'What is something that one of you wants to do some day?', or whatever, and then kind of go off that. And I think that the more that the students are engaged in it… [I would teach engineering by] having the students come up with their own ideas. So, you know, for example, saying like, 'All right. What do we want to do?', and one student says, 'I want to create shoes that hover' or something." (Monty Interview 2)
	Using mathematics	"You've tested your idea, tested it somehow in your mind or you test the concept on paper with more rigorous math." (Anthony Interview 1)
	Engineering is integrated	"I feel like engineering is kind of like, the combination of all of those [physics, chemistry, and biology], or the combination of different ones. Like definitely its's talking about circuits or fiber optics, it'd be physics, a little bit of chemistry and probably not too much bio. But like, for example, if you're doing biomedical it'd definitely be physics bio and chemistry, so all of those. And then I just feel like each type of engineering is just a different combination of the different sciences." (Ralph Interview 1)

	"Isaac Asimov… he was talking about how in order to be creative, like you need a – you can't just focus on engineering. If you want to be a creative engineer, you need to take art class, English class, social studies; you just need to get information from everybody; like a buffet of ideas. And then they'll all connect." (Rick Interview 3)
	"We're totally integrated… In our program, we're actually integrating all, you know, curriculum, STEAM. And it's beyond that, too, because we don't just do science, technology, engineering, art, and math. We also require students do a lot of writing. We have a lot of historical context to the things we're teaching them. So I think it integrates even beyond steam in our program. And they really need to have like a working knowledge of all of those in order to be successful in the program." (Dana PBEA Teacher Focus Group)
Thinking like an engineer	"Engineering is all around us. You just have to… it's just a way of solving problems that's really fast and efficient and, you know, it's just calculated thinking… I feel like everybody engineers a little. You make something, it's kind of engineering." (Nick Interview 2)
	"I don't think a way an engineer thinks' I don't think mechanically. I think very more open and free… I feel like they think in shapes or something… Here's a square, and this is a block and they want things to be very neat, and square and tidy. I think oh circles, blobby shapes, colors everywhere flying." (Rick Interview 2)
	"I don't think you have to have a skill set in a specific area in order to be an engineer, you just have to have a mindset. You have to have a way of thinking about problems and how you solve them. Like I think elementary school kids can be engineers if you show them how to approach problem solving in a kind of methodical careful way, and analyze mistakes and kind of iteratively change their ideas and their solutions. So I don't think it has to be something that's only reserved for professionals doing esoteric engineering feats, I think it's just a way of thinking about problems." (Zeb Interview 3)
	"The one point of engineering is to get students to think critically, even if they don't go into engineering. Or even if they don't go into science. Because thinking critically can help you anywhere." (Xandra Interview 4)

Comparing participant frequency and use. Once a list of the various aspects of engineering design had been established and these had been mapped to each participant, frequencies were calculated to determine which aspect, how many aspects, as well as how often each aspect was discussed by an individual throughout the data. This was done to determine if there were particular aspects of engineering design that were more or less commonly used by participants overall. The total occurrences that a participant used each aspect of engineering design throughout all the data was calculated for all participants. An occurrence is a single unit of analysis, which consisted of participant talk about a particular aspect of engineering design with enough context to make clear to the researcher which aspect was being discussed without looking outside that particular unit of analysis. These numbers demonstrate how often a participant discussed an aspect of engineering design across the data. Findings are discussed by aspect as either high (discussed more than 20 times), medium (discussed between 10 and 20 times), or low (discussed less than 10 times) *frequency* by a participant. High, medium, and low *use* was also established depending on the number of participants who discussed each aspect.

Overall frequency and use. Frequencies were also calculated for how often the aspects were discussed across all participants in an effort to gauge the most common aspects of engineering design among individuals along the learning-to-teach continuum. The total number of occurrences that each aspect of engineering design was mentioned throughout the data and across all participants was analyzed. This information demonstrates how often a particular aspect was discussed in the data overall and was calculated by finding the total units of analysis where that aspect was mentioned across all participants. The number of participants (out of the total 27) who discussed each aspect of engineering design at least once was also analyzed. These totals demonstrate how broadly a particular aspect of engineering design was identified across participants.

The information yielded through level 1 analyses was used to provide insight into the aspects of engineering design that were more and less commonly discussed by participants overall, and guided level 2 analyses—creating conceptual categories of engineering design. At this point in the analysis process, additional variables (e.g., group, background, experience, etc.) were not taken into consideration, and participants were not differentiated in any way.

Level 2 Analysis

The second level of analysis consisted of using the aspects of engineering design that were obtained in the previous analyses to generate "conceptual categories" or "categories of description" (Marton 1981; 1986). The data was broken out by participant and instance (a single interview and/or associated concept map) so the aspects of engineering design from each particular point in time could be analyzed. This was done because looking at a single participant over three or four interviews was thought to provide an inaccurate picture of an individual's understanding and view of engineering design at a particular time—views and understandings can and often did change over time. An aspect was included in a participant's view of engineering design if it was discussed at least once in a particular instance. Aspects were given equal weight regardless of the frequency in which they were discussed (e.g. *problem or need*—discussed 5 times—is counted the same as *secondary effects*—discussed only once). This was done to ensure that some aspects of engineering design, which were discussed more frequently, did not skew analyses or the development of conceptual categories.

In examining the data, the researcher looked for "the most distinctive characteristics … [and] structurally significant differences that clarify how people define some specific portion of the world", in this case, engineering design (Marton, 1986, p.

34). The goal was to identify the “fewest, logically related categories required to describe the totality of variation discerned in the pool of experience” (Case & Light, 2011, p. 199). To do so, the data were sorted into tentative categories, borderline cases were examined, and the criteria of attributes for each category were developed. Through several iterations of this process, concrete conceptual categories were created that had established criteria for inclusion with critical dimensions of variation, which created a “system of meaning,” or “outcome space,” of engineering design (Case & Light, 2011; Marton 1986; Marton & Pong, 2005).

Six conceptual categories of engineering design were established through level 2 analyses: *Basic NGSS, Business or Product Focused, Knowledge and Skills, Creative Thinking, Human Centered, and Improvement*. Each conceptual category and the criteria for inclusion in each is shown in Table 3h below. Participants were classified into a particular category if they discussed a majority (e.g., they discussed at least four out of seven aspects of engineering design associated with the *Knowledge and Skills* category, or three out of four aspects associated with the *Human Centered* category) of the aspects of engineering design associated with that category in an interview and/or in their associated concept map—called an “instance”. Participants were classified into at least one conceptual category per instance, with some participants discussing enough aspects of engineering design to be classified into all six categories at a particular instance. The first category—*Basic NGSS*, discussed below—was the most common and was therefore not a focus in level 2 analyses beyond being the most base-level conceptual category that participants were classified under.

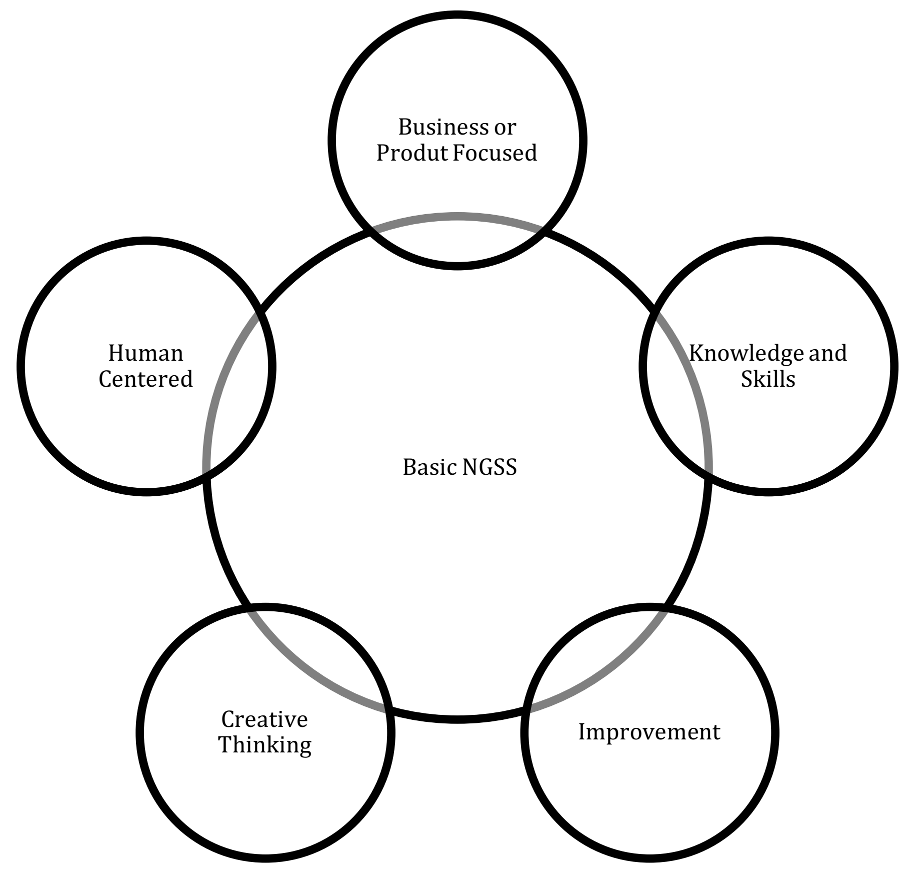


Figure 3d. Representation of the conceptual categories of engineering design

Basic NGSS. The *Basic NGSS* category includes the basic aspects of engineering design that are part of the *Next Generation Science Standards* (NGSS Lead States, 2013): define a problem or need, identify constraints, develop solutions, optimize the solution, and the iterative design process. If participants discussed at least three of these *Basic NGSS* aspects and did not discuss a substantial number of aspects from other conceptual categories, they were included in the *Basic NGSS* category for engineering design.

All participants across all instances in the data identified at least three aspects of engineering design from the *Basic NGSS* category, however, there were only six instances across five participants who *only* discussed the aspects of engineering design from the *Basic NGSS* category without discussing a substantial number of aspects from other categories (see Figure 3d above for a graphic representation of the six conceptual categories). Because all participants identified the aspects of engineering design for the *Basic NGSS* category, the other five categories were the focus of this study since they provided more robust descriptions of the various understandings of engineering design from the data.

Business or Product Focused. The *Business or Product Focused* conceptual category of engineering design is distinguished by seven aspects of engineering design that were identified in level 1 analyses: identifying constraints, the scope of design, subproblems, competition, simplicity, final product, and physical object. These aspects all relate to a business or product focused view of engineering design because they highlight the importance of working within the constraints and scope of the engineering project at hand and breaking down the project into smaller, more manageable goals. There is also a focus on creating a physical object or final product that is the simplest or most efficient and is better than the competition's. If participants discussed at least four of the seven aspects of engineering design listed above, they were classified into the *Business or Product Focused* conceptual category of engineering design.

Knowledge and Skills. The *Knowledge and Skills* conceptual category of engineering design is distinguished by seven aspects of engineering design: research the problem, research solutions, prior knowledge and experience, based on science, engineering is integrated, using mathematics, and using technology. These aspects all relate to using one's knowledge and skills in engineering design because they highlight how one needs to utilize prior knowledge and skills (from various areas including science, mathematics, technology, or other subject) or seek more knowledge and skill (usually through research) through the engineering design process. Five participants in five separate instances identified at least four of the seven aspects of engineering design to include them in the *Knowledge and Skills* conceptual category of engineering design. 20 participants across 27 instances identified a substantial number of aspects of engineering design from the *Knowledge and Skills* category in addition to those from at least one other category.

Creative Thinking. The *Creative Thinking* conceptual category for engineering design is distinguished by four major aspects of engineering design: aesthetics, creativity, inspiration, and thinking like an engineer. These aspects all relate to thinking in a way that allows one to solve problems creatively by generating innovative ideas that draw on one's creative and artistic skills.

Human Centered. The *Human Centered* conceptual category of engineering design is distinguished by four aspects of engineering design: thinking about the user, communication, secondary effects, and collaboration. All of these aspects of engineering design highlight the human element of engineering design, which includes the need to think about how the design process involves working with and communicating with others and how the product should consider people (either through personal use or as an effect of others' use).

Improvement. The final conceptual category for engineering design is *Improvement*. This category is distinguished by five aspects of engineering design:

comparing solutions, optimal design, testing and evaluation, evolutionary design, and never ending process. All of these aspects of engineering design highlight the desire to improve engineering solutions through constantly testing, comparing, and evaluating them.

Table 3h

Conceptual Categories of Engineering Design

Conceptual Category	Criteria for Inclusion
Basic NGSS	This category includes references to the aspects of engineering design that are included in the basic description of engineering design provided in the *Next Generation Science Standards* (NGSS Lead States, 2013). These aspects are 1) Define a problem or need, 2) Identify constraints, 3) Develop solutions, 4) Optimizing the solution, and 5) The iterative design process. Inclusion in this category requires that participants discuss at least 3 of these aspects of engineering design, without discussing many other aspects that are critical for the inclusion in other conceptual categories.
Business or Product Focused	This category is distinguished by seven aspects of engineering design: 1) Identifying constraints, 2) The scope of design, 3) Subproblems, 4) Competition, 5) Simplicity, 6) Final product, and 7) Physical object. These aspects all relate to a business or product focused view of engineering design because they highlight the importance of working within the constraints and scope of the engineering project-at-hand and breaking down the project into smaller, more manageable goals. There is also a focus on creating a physical object or final product that is the simplest or most efficient and is better than the competition's. Inclusion in this category requires that participants discuss at least 4 of these aspects of engineering design.
Knowledge & Skills	The Knowledge and Skills category is distinguished by seven aspects of engineering design: 1) Research the problem, 2) Research solutions, 3) Prior knowledge and experience, 4) Based on science, 5) Engineering is integrated, 6) Using mathematics, and 7) Using technology. These aspects all relate to using one's knowledge and skills in engineering design because they highlight how one needs to utilize prior knowledge and skills (from various areas including science, mathematics, technology, or other subject) or seek more knowledge and skill (usually through research) through the engineering design process. Inclusion in this category requires that participants discuss at least 4 of these aspects of engineering design.
Creative Thinking	The Creative Thinking category is distinguished by four major aspects of engineering design: 1) Aesthetics, 2) Creativity, 3) Inspiration, and 4) Thinking like an engineer. These aspects all relate to thinking in a way that allows one to solve problems creatively by generating innovative ideas that draw on one's creative and artistic skills. Inclusion in this category requires that participants discuss at least 3 of these aspects of engineering design.

Human Centered	The Human Centered category is distinguished by four aspects of engineering design: 1) Thinking about the user, 2) Communication, 3) Secondary effects, and 4) Collaboration. All of these aspects of engineering design highlight the human element of engineering design, which includes the need to think about how the design process involves working with and communicating with others and how the product should consider people (either through personal use or as an effect of others' use). Inclusion in this category requires that participants discuss at least 3 of these aspects of engineering design.
Improvement	The Improvement category is distinguished by five aspects of engineering design: 1) Comparing solutions, 2) Optimal design, 3) Testing and evaluation, 4) Evolutionary design, and 5) Never ending process. All of these aspects of engineering design highlight the desire to improve engineering solutions through constantly testing, comparing and evaluating them. Inclusion in this category requires that participants discuss at least 3 of these aspects of engineering design

Multiple Conceptual Categories. As mentioned above, many participants discussed many aspects of engineering design that would classify them in more than one conceptual category. Some participants were classified into two, three, four, and sometimes five (out of the possible five distinct categories; not including Basic NGSS) conceptual categories in a particular instance. Each of these combinations represent a slightly different understanding of engineering design and each added conceptual category represents another level of complexity added to that participant's view of engineering design at that particular instance. For example, a participant who identified aspects of engineering design from both the Business or Product Focused conceptual category as well as the Human Centered category may have a deeper understanding of the need for collaboration and thinking about the user when developing a product for the market.

Level 2 analyses developed six major conceptual categories for engineering design: *Basic NGSS, Business Focused, Knowledge and Skills, Creative Thinking, Human Centered, and Improvement*. Some participants only discussed enough aspects of engineering design in a particular instance to be classified into only one of these categories. In other instances, participants discussed additional aspects of engineering design, which allowed them to be classified into one or more of the "multiple conceptual" categories. It was theorized that as the number of conceptual categories that an instance can be classified into increases, the participant conveyed a more complex understanding of engineering design at that instance. Each combination of multiple categories that was represented in the data and the features of engineering design that were and were not represented in them will be discussed in more detail in the findings. With the exception of the few instances of integrated understanding—when all the conceptual categories for engineering design were represented—participants did not indicate through their concept maps and/or interviews that they understood all complexities that go into engineering design.

Level 3 Analysis

The third level of analysis took an experimental phenomenological perspective by taking the *outcome space*, garnered from level 2 analyses, and comparing it with specific aspects of the context and participants. The context of this study was the level of experience that participants had with engineering and/or science in the classroom—which includes formal or informal instruction on the *Next Generation Science Standards* (NGSS Lead States, 2013). *Experience* includes where a participant was along the learning-to-teach continuum and their prior experience with formal and informal engineering (e.g., courses on engineering, or informal engineering experiences) and their familiarity with engineers. Another factor of the participants' context, whether their school placement had an engineering component, was also analyzed. Lastly, demographic information about participants (academic major, gender, and ethnicity) was also compared with conceptual categories to see if patterns emerged. It is important to note that while I did include practicing teachers and teacher educators in these analyses, their data was a limiting factor since they only participated in one focus group interview and did not complete their own concept maps of engineering design. Because of this their data may not contain the richness that the prospective and preservice teacher data did.

Comparing Experience Along the Learning-to-Teach Continuum. First, the conceptual categories were analyzed by overlaying the context of *experience* on the data. To do this, I grouped participants by where along the learning-to-teach continuum they were at the time of the study (prospective, preservice, practicing, or teacher educator), which provided one perspective on how much experience a participant had with science and/or engineering either in the classroom or in other contexts. Because the prospective and preservice teacher participants were interviewed and/or created concept maps at multiple times throughout the study year, their final interview and concept map data was compared to the focus group data from the practicing teachers and teacher educators. This was done to make a comparison between these groups after they had some background and experience in the classroom, but at varying intensities—the preservice teacher education program was much more intensive than the internship over the course of the study year, therefore the full range of experience (from little experience in the classroom to many years of experience) could be examined.

Comparing Formal and Informal Engineering Experience. As another component of level 3 analyses, I looked at other indicators of participants' experience with engineering outside of the classroom, such as courses taken, informal engineering experiences, familiarity with engineers, etc. These measures of experience were gathered during their initial interviews; researchers asked about their experience with engineering and probed for courses taken, informal engineering done, and their familiarity with any engineers. Similar to how conceptual categories were compared along the learning-to-teach continuum, the final instances (interviews and concept maps) were used to represent the conceptual categories of the prospective and preservice teachers.

Comparing Context and Demographics. Lastly, the conceptual categories of participants were analyzed based on their school placement context and demographic information, which they self-reported before the start of the study as part of the application process for the scholarship programs. The *context* that was analyzed here was the school or placement information for all participants and whether it included an engineering component. All school placements that included engineering also had science components, however, some placements were only science and did not explicitly incorporate engineering. In some quarters, prospective teachers chose not to go into classrooms, and during the fall quarter, preservice teachers were, for the most part, observing and not student teaching—unless placed at the Project-Based Engineering Academy—and therefore, their placement for that quarter was not included in this analysis of classroom context.

Demographic information was only collected systematically from prospective and preservice teacher participants, however, some practicing teachers mentioned their academic majors when asked about their background in the focus group interviews. The overlay of these *demographic* factors (academic major, gender, and ethnicity) with the conceptual categories was also analyzed to determine if there was any relationship between the two. By looking at these additional context and demographic categories, it allowed me to identify potential underlying factors that might have influenced an individual's inclination to hold one conception over another or the complexity of their understanding of engineering design and can illuminate what might have been an impetus for changing conceptions of engineering design.

Summary

Analyses proceeded through three major levels. First, all of the data (including individual and focus group interviews, as well as concept maps) were analyzed to identify the wide range of aspects of engineering design that were discussed by participants. Thirty separate aspect of engineering design were identified and described above. These aspects of engineering design were then grouped into meaningful categories that described a particular type of understanding of engineering design in level 2 analyses. Six major conceptual categories of engineering design were established based on what emerged from the data: *Basic NGSS, Business or Product Focused, Knowledge and Skills, Human Centered, Improvement,* and *Creative Thinking*. All of these conceptual categories were described and the criteria for inclusion in each was established.

Additionally, in level 2 analyses, the various combinations of conceptual categories that an individual participant could include within at a given instance was also described and inferences on the complexity of understanding of engineering design were made. It was theorized that the more conceptual categories that a participant included in his or her discussion, the more complex and integrated his or her overall understanding of engineering design was at that particular instance. The inclusion in the various conceptual categories was then used as a basis for the final level of analysis.

Because this study included participants from many different backgrounds and contexts along the learning-to-teach continuum, analyses benefited from looking more deeply across these variations. The conceptual categories included in participants' talk at each instance was first examined for prospective and preservice teachers (who participated in multiple interviews throughout the study year) over time to see if time and experience in the classroom had an effect on their understandings of engineering design. Next, all groups of teachers along the learning-to teach continuum were compared to determine if there were differences between or within groups. Further, context factors were examined as they related to a participant's experience with engineering in the classroom—some classroom placements had an engineering component in addition to science, while other did not. Lastly, demographic factors of participants were examined to determine if academic major, gender, or ethnicity had any relationship to a participant's conceptual categories.

Chapter 4: Findings

Through the three analytic cycles described previously, I identified findings that speak to multiple levels of engineering design and answer the following research questions: (1) What conceptions of engineering design did teachers along the learning-to-teach continuum hold? (2) What characteristics or experiences of participants appeared to influence their understanding of engineering design, such as their engineering experience, other STEM experiences, or personal background? First, I present the various aspects of the engineering design process discussed by participants along the learning-to-teach continuum. Second, I identify the various conceptual categories of engineering design, or combinations of those categories, that individual participants held. And last, I determine the relationships between the various contexts and backgrounds of participants and their conceptual categories of engineering design. Each of these three levels of findings are discussed in greater detail below.

Level 1 Findings: Aspects of Engineering Design

The first set of findings presents the many aspects of engineering design identified by participants in their interviews and concept maps, determined through the first cycle of data analysis. I also present the number of times a given aspect of engineering design was identified by participants in two ways: the usage by participants (includes all instances for a single participant), and the frequency of use by participants. These two measures demonstrate whether aspects were used by participants overall (their use), and how frequently they were used in discussion (their frequency). Overall findings across all participants are discussed, as are findings at the participant level.

Chapter 4: Findings

From analyses of all participant data, I constructed a list of 30 aspects of engineering design. I identified 14 of these aspects from my review of the *Next Generation Science Standards* [*NGSS*] (NGSS Lead States, 2013), 10 aspects from a review of relevant literature on engineering design (discussed in Chapter 2), and an additional 6 aspects from data coded during level 1 analyses (see Table 4a below for the complete list).

Table 4a

Identified Aspects of Engineering Design by Source

Source	**Identified Aspect**
1. NGSS Component 1 *Defining and delimiting engineering problems*	Problem or need Thinking about the user Research Identifying constraints The scope of design Subproblems
2. NGSS Component 2 *Designing solutions to engineering problems*	Communication Developing solutions Research
3. NGSS Component 3 *Optimizing the design solution*	Comparing solutions Secondary effects Design process Testing and evaluating Optimal design
Added Aspects— *From Review of Literature*	Competition Prior knowledge and experience Based on science Creativity Aesthetics Simplicity Collaboration Evolutionary design Final product Never ending process
Added Aspect— *From Coding of Data*	Using technology Physical object Inspiration Using mathematics Engineering is integrated Thinking like an engineer

Once these 30 aspects of engineering design were established, I calculated the frequency and usage of these aspects overall and by individual participant. More specifically, below, I discuss patterns in the use and frequency of aspects of engineering design across all participants in the study. Then, I present patterns in use and frequency by individual participant. It is important to note that during these level 1 analyses, participants were not segregated based on group, background, etc. All instances from all participants were examined to provide a comprehensive picture of their overall understanding of engineering design in this study.

Overall Findings: Use

I calculated the overall use of each aspect of engineering design by determining how many participants mentioned that aspect at any point in the data collection process. If a participant mentioned a given aspect at least once, that aspect was counted as one; if she or he did not, that aspect was not counted. The number of participants who explicitly discussed a given aspect of engineering design varied widely, ranging from 27 participants (all of them) to nine. Looking at how many participants discussed each aspect of the engineering design process provides insight into how widely or narrowly they might be considered by participants overall. For example, aspects that were discussed by a majority of participants might be more important or understood by more groups of participants along the learning-to-teach continuum than those aspects that were mentioned by very few participants.

High use. I found that some aspects of engineering design were discussed by participants far more often than others. Of the total 30 aspects, five were discussed by all

27 participants: *identifying constraints, problem or need, design process, testing and evaluating*, and *physical object*. Four of these five aspects of engineering design are discussed in the *Next Generation Science Standards* (NGSS Lead States, 2013), with the exception of *physical object*, which was added during coding. These aspects of engineering design exemplify the basic process of engineering that is done to create something (e.g., a physical object): A problem is identified, constraints are considered, and designs are tested and evaluated iteratively before creating something. One preservice teacher participant used all of these aspects of engineering design in describing their her concept map:

> It's kind of like identifying the problem here. And so that kind of goes hand-in-hand with the constraints. I just listed a couple, be it money, materials, time, or size. Um, I think there's more than that, but those are some examples of constraints. I think the next step after your, like knowing your problem and the constraints, I would say brainstorm solutions -- when you do design and all the while considering problems and constraints. You always are going back to that. After design, I would say you assess your design, maybe test it on a computer or just look for potential weak spots. So that could lead to more design, kind of repeat the process. You would then manufacture, construct it, again assess to see if it meets problem, problem and constraint requirements. If necessary, go back to design. Repeat until you have your solution or whatever best fits the constraints and problems. (Caitlyn, Final Interview)

A practicing teacher also used all of these aspects of engineering design when describing how well the given example concept map aligned with the view of engineering design of the Project-based Engineering Academy, where she taught:

> They're given a task, a problem—whatever you want to call it. They're given some objective that they have to attain. They're given time to do their brainstorming concept design. There's obviously time and resource constraints. Once they're okay'd through that step, they're designing their own aesthetic. Once their designs are done, then they manufacture…which, that's the only step missing. So after design, they should have kind of like the prototype section, I think—prototype or manufacturing….After their design is prototyped, then you would test it. So for us, the kids, after they test them, it doesn't work—obviously they have to go back and make it better to make it right, modify it, and then it doesn't necessarily take them up to the very top problem again. It might like bring them to a mid-step, you know, in the cycle where like say their [circuit] board doesn't work and they can't program it. They only have to go back and fix the board. They don't have to go back and fix the rest of the body of it. So, I think it's pretty close. (Dana, Focus Group)

Other frequently discussed aspects of engineering design included the following: *based on science* (26 participants), *using technology* (26 participants), *communication* (25 participants), *developing solutions* (25 participants), *optimal design* (25 participants), *final products* (24 participants), *creativity* (22 participants), *comparing solutions* (21 participants), and *research solutions* (20 participants). Many participants discussed the need to utilize science and technology (including manufacturing technology) to do engineering. Many also discussed the process of developing engineering solutions by brainstorming and researching solutions, as well as using creativity (usually to develop novel solutions). After solutions are generated, participants discussed the need to compare solutions to find the best to move forward with and to then communicate their design either through writing, talking, or creating drawings or models of it. Finally, participants noted the importance of creating an optimal design that solves the engineering problem best, usually in the form of a final product. One can see the use of some of these aspects of engineering design in the quotes above, including *using technology*, *communication*, *developing solutions,* and *optimal design.*

Medium use. I found that approximately two-thirds of participants (fewer than 20) discussed the following aspects of engineering design: *research problem* (19 participants), *subproblems* (19 participants), *thinking about the user* (19 participants), *prior knowledge and experience* (19 participants), *collaboration* (19 participants), *using mathematics* (18 participants), and *never ending process* (16 participants). These aspects of engineering design were designated medium use. They are considered more complex since many of them are only discussed in only the higher grade bands of the *NGSS*. One, *research problem*, is not discussed in the *Next Generation Science Standards* (NGSS Lead States, 2013) until middle school (MS-ETS1-1). Another, *subproblems,* is only part of the more complex high school engineering design standards (HS-ETS1-1). A third aspect, *using mathematics,* is implicitly included in the high school standards as the practice "using mathematics and computational thinking" that students are required to use when testing and evaluating their engineering designs.

One prospective teacher participant described three of the four most commonly used aspects of engineering design categorized as medium use—*research problem*, *subproblems*, and *thinking about the user*—in her description of her concept map on engineering design:

> You identify the problem. The problem can be that your existing technology is not good, maybe it costs too much, maybe it's dangerous. It's not easy to use, it's not -- it's solving a problem but maybe you created another one [a subproblem]. And then there's lacking technology, like there's something, like there's [a] new phenomenon. Like let's say even something like global warming, and all of a sudden you're like okay there's -- I don't have any technology that I can use now, in this new environment, you know whether that be to reduce emissions or renewable energies. So yeah, so those are like -- those are kind of like saying like a problem can be two different things. It can be deficient existing technology or you're lacking technology, so you need to gather knowledge about the problem itself, so you can understand the problem and find where the deficits are. (Xandra, Winter Interview)

Using one's *prior knowledge and experience* and *collaborating with others* are not only practices used in engineering design, but in other subjects as well, and are commonly used in classrooms to help facilitate learning. The aspect of engineering design, *thinking about the user*, is a specific kind of constraint that thinks about who will use the design, how it will be used, and other things the user will take into consideration in the design. This kind of thinking, while not present in the *NGSS,* is present in higher-level engineering design, such as undergraduate engineering programs. Engineering design as a *never ending* process is an idealistic and unrealistic view of engineering where participants discuss how engineers can continue revising their designs indefinitely because, as prospective teacher Monty stated, “I don’t think that you could ever get to a point where something couldn’t be better” (Post-Summer Interview).

Low use. Finally, aspects of engineering design that were discussed by a minority of participants were the following: *evolutionary design* (12 participants), *inspiration* (12 participants), *thinking like an engineer* (11 participants), *secondary effects* (10 participants), *simplicity* (10 participants), *engineering is integrated* (10 participants), *the scope of design* (9 participants), *competition* (9 participants), and *aesthetics* (9 participants). Some of these aspects of engineering design focus on the things engineers must take into consideration when designing, including the scope of the design, the way it looks, efficiency of the design, potential effects of using the design or product, and aspects of competition, such as creating a better solution than others. These aspects of engineering design that were considered low use recognize that engineering can integrate multiple fields (more than just science) and that often times engineers build on the designs of others and just make small, iterative changes (*evolutionary design*). Last, these aspects also include how engineers think in a certain way (e.g., problem solving, etc.) and often times rely on inspiration or an idea, rather than first identifying a problem or need.

Monty, in her initial interview, described engineering in this way, using the *inspiration* and *thinking like an engineer* aspects:

> I think it is innovation. I think engineering is coming up with an idea and creating it out of, you know, like knowledge you've had before or resources you've had before. Something like that. It involves a lot of critical thinking and being original.

Overall, those aspects that were discussed by most participants tended to be included in the *Next Generation Science Standards* (NGSS Lead States, 2013) or are commonly used in professional engineering, and engineering or engineering-related courses or activities. Those aspects that were discussed by a fewer number of participants tended to be aspects of engineering design that are more complex, less frequently used in engineering contexts, and/or more specific to a particular subset of engineering.

Overall Findings: Frequency

The frequency that each aspect of engineering design was discussed was calculated by counting each occurrence across all instances (including all their interviews and concept maps) in the data (see again Table 4b). As one might expect, I found that some aspects of engineering design were discussed far more frequently by participants overall than others. Looking at frequency of the discussion of these aspects gives an idea of not only whether they were used by participants, but how often, which might indicate the importance (or lack thereof) of these aspects of engineering design as viewed by the participants in this study along the learning-to-teach continuum.

Table 4b

Total Frequency and Use by Aspect of Engineering Design

Aspect of Engineering Design	TOTAL Use	Level of Use	TOTAL Frequency	Level of Frequency
Problem or need	27	High	386	High
Physical Object	27	High	290	High
Testing and evaluating	27	High	282	High
Design Process	27	High	277	High
Identifying constraints	27	High	273	High
Based on Science	26	High	175	Medium
Using Technology	26	High	137	Medium
Developing solutions	25	High	338	High
Communication	25	High	194	Medium
Optimal design	25	High	119	Medium
Final product	24	High	77	Medium
Creativity	22	High	91	Medium
Comparing solutions	21	High	76	Medium
Research Solutions	20	High	78	Medium
Collaboration	19	Medium	87	Medium
Research Problem	19	Medium	82	Medium
Thinking about the user	19	Medium	82	Medium
Subproblems	19	Medium	47	Low
Prior knowledge and experience	19	Medium	38	Low
Using mathematics	18	Medium	59	Low
Never ending process	16	Medium	35	Low
Inspiration	12	Low	49	Low
Evolutionary design	12	Low	31	Low
Thinking like an Engineer	11	Low	32	Low
Engineering is Integrated	10	Low	33	Low
Secondary effects	10	Low	25	Low
Simplicity	10	Low	19	Low
Aesthetics	9	Low	32	Low
Competition	9	Low	22	Low
The scope of design	9	Low	14	Low

High frequency. Some aspects of engineering design were discussed by participants very often; throughout the data, some aspects of engineering design were discussed much more than others. Aspects were considered high frequency if they were discussed more than 210 times total. This means that they were potentially discussed three times in each instance by participants (there were a total 70 instances in the data). I found the high frequency aspects of engineering design to be the following: *problem or need* (386 occurrences), *developing solutions* (338 occurrences), *physical object* (290 occurrences), *testing and evaluating* (282 occurrences), *design process* (277 occurrences), and *identifying constraints* (273 occurrences).

Several participants used all of these high frequency aspects of engineering design in their discussion. Patty, a teacher educator, provided a concise description of her view of engineering design that incorporated all of these high frequency aspects:

> Well, you ask yourself what is the challenge, or what is the problem, and you look at what you have at hand to... try to figure out a solution. For instance, I'm just thinking about...let's just take the egg drop. I mean, what materials do you have, what time do you have, what constraints do you have. And then you...build something, a prototype, test it, rebuild it, test it again, and you continue in that until you meet success. (Patty, Focus Group)

With the exception of *developing solutions*, all of these high frequency aspects of engineering design were also those that were discussed by all 27 participants. This indicates that these were not only important aspects of engineering design for some individuals, but that they were important for all participants across the learning-to-teach continuum. They also align with the main parts of engineering design as discussed in the *Next Generation Science Standards* (NGSS Lead States, 2013).

Medium frequency. Aspects of engineering design discussed by participants overall at a medium frequency were those discussed at least more than once per instance (70 times) up to three times per instance (210 times). It is important to note that these boundaries were established to create clearer distinctions between the levels and do not guarantee that an aspect was, in fact, discussed across all instances in the data. Those aspects of engineering design that fell within this range included the following: *communication* (194 occurrences), *based on science* (175 occurrences), *using technology* (137 occurrences), *optimal design* (119 occurrences), *creativity* (91 occurrences), *collaboration* (87 occurrences), *research problem* (82 occurrences), *thinking about the user* (82 occurrences), *research solutions* (78 occurrences), *final product* (77 occurrences), and *comparing solutions* (76 occurrences).

Many of the above aspects of engineering design are specific to professional engineering, which some participants might have been familiar with, while other participants might have had no experience or knowledge of them. Some aspects, such as *collaboration*, *creativity*, and *communication*, are aspects of engineering and other disciplines, which many teachers use in their classrooms. Other aspects, such as *based on science*, *using technology*, and *final product,* are aspects of engineering commonly used in engineering courses or activities—especially in traditional engineering-based science activities where students build something based on principles in science. Prospective teacher, Zeb, described what he thought engineering was using these aspects of engineering design:

> Engineering is working with technologies that exist in order to solve problems and make it practical and marketable, if that's your goal. Or to make something cost effective and to solve a problem by using whatever technologies, electronics or mechanics or computers, you know, biological systems… I think there's… an expectation that you get an end product out of engineering. (Winter Interview)

Low frequency. I categorized those aspects of engineering design discussed by participants less than once per possible instance (less than 70 times) as low in frequency. In other words, there was no possibility that all participants across all instances in the data could have discussed these aspects of engineering design. These low frequency aspects of engineering design are the following: *using mathematics* (59 occurrences), *inspiration* (49 occurrences), *subproblems* (47 occurrences), *prior knowledge and experience* (38 occurrences), *never ending process* (35 occurrences), *engineering is integrated* (33 occurrences), *aesthetics* (32 occurrences), *thinking like an engineer* (32 occurrences), *evolutionary design* (31 occurrences), *secondary effects* (25 occurrences), *competition* (22 occurrences), *simplicity* (19 occurrences), and *the scope of design* (14 occurrences).

The low frequency group is the largest group of aspects of engineering design with 13 aspects, ranging in their frequency of discussion from 59 occurrences to 14 occurrences. Many of these aspects are not part of the *Next Generation Science Standards* (NGSS Lead States 2013) and are, instead, more complex or specific parts or considerations of the engineering design process that many participants might not have had experience with. Similar to the findings for overall usage above, these kinds of aspects of engineering design tended to be discussed less by participants and by fewer participants. One practicing teacher, Josh, described the way students engage in engineering at the Project-based Engineering Academy using the *aesthetics, secondary effects,* and *simplicity* aspects of engineering design:

> I would say it's something similar to that—like all the math and science and art, as well, applying [those] to actually making things. And the one thing that this place has that a lot of [others] don't is that we're actually making stuff here, where a lot of like—there's a lot of architects that go out into the world. There are a lot of engineers, as well, that go out and they have no idea. They've never actually made anything. So they just draw a picture, and then someone else deals with it and… there's this huge amount of waste, like massive amounts of like wasted dollars on people that have never actually built stuff that are designing it. So, that's one huge bonus to this program, I think. (Focus Group).

Participant Level Findings: Use

As described above, participants' usage of aspects of engineering design was calculated by counting whether or not each discussed a given aspect at least once throughout the data. If she or he did, that aspect was counted as one; if she or he did not, the aspect was not counted in the total. Table 4c, below, shows the total usage of the aspects of engineering design by each of the 27 participants (rather than by the entire groups of participants as presented above). The table makes clear that no one participant discussed the full range of aspects across the data collected. Of the 30 identified aspects of engineering design, 12 to 28 aspects were discussed by a particular participant throughout the data. This means that some participants held quite complex views of engineering design—indicated by their use of most of the aspects of engineering design—while others did not have as sophisticated or complex of a view of it—indicated by their use of fewer aspects throughout the data. This latter point is discussed in greater detail below in level 2 findings.

Table 4c

Individual Participant's Use of Aspects of Engineering Design

Participant	**Aspects of Engineering Design Used (out of 30)**	**Participant**	**Aspects of Engineering Design Used (out of 30)**
Adam	22	Macy	20
Anthony	19	Molly	18
Caitlyn	20	Monty	26
Carlos	23	Nick	24
Dana	21	Patty	12
David	22	Ralph	26
Haylee	23	Rick	23
Jasmine	12	Sally	13
Josh	18	Sandra	20
Kari	21	Sasha	26
Kayla	23	Saul	24
Ken	18	Xandra	28
Kristy	22	Zeb	27
Kurt	19		

Participant Level Findings: Frequency

Similar to that discussed above, the frequency of an individual participant's discussion of aspects of engineering design was calculated by counting each occurrence that a participant talked about a particular aspect of engineering design in an interview or concept map. An occurrence is a single unit of analysis (introduced in the Analysis section above) where the aspect was discussed. All occurrences were counted across each participant's set of data (all of their interviews and/or concept maps) to give a total count that each aspect of engineering design was discussed by participant. The discussion of a single aspect of engineering design among all participants ranged from one—although many were not discussed at all by participants—to 37 occurrences.

Again, the limitations of the data collection methods used for practicing teachers and teacher educators most likely affect these findings since they participated in only a single focus group interview and did not construct their own concept map of engineering design. Because of this, their data were not as rich and did not contain as many opportunities for the participants in these groups to discuss the many aspects of engineering design. Despite this, they are included in analyses and are discussed in these findings.

High frequency. I designated aspects of engineering design that were discussed more than 20 times by a single participant as high frequency. Four participants each discussed one aspect of engineering design at a high frequency: Adam, *problem or need*; David*, developing solutions*; Nick, *problem or need*; and Zeb*, physical object*. The focus on a single aspect of engineering design indicates that these participants placed a high importance on that specific aspect. Three of the four aspects of engineering designated high frequency align with the three major parts of engineering design as described in the *Next Generation Science Standards* (NGSS Lead States, 2013): defining and delimiting engineering problems (*problem or need*), designing solutions to engineering problems (*developing solutions*), and optimizing the design solutions (*testing and evaluating*). The fourth high frequency aspect focused on by Zeb, *physical object*, highlights this individual's view of engineering design as the process of creating something physical.

Four participants discussed two to five aspects of engineering design at a high frequency: Carlos, Saul, Monty, and Kayla. Carlos discussed five aspects at a high frequency: *problem or need, developing solutions, design process, testing and evaluating,* and *physical object.* Similar to the participants above, most of these aspects of engineering design that Carlos focused on are in line with the *NGSS,* as well as highlight his view of creating a physical object as the goal of engineering design. Saul discussed two aspects at a high frequency: *problem or need* and *developing solutions*. These, too, are in line with the *NGSS*, however, Saul did not discuss as many of these aspects as Carlos did. This might mean that Saul did not have quite as broad of an understanding or view of engineering design compared to other participants. Kayla discussed two aspects of engineering design at a high frequency: *problem or need* and *testing and evaluating*. She demonstrated recognition of two of the main parts of the *NGSS* description. Monty discussed three aspects of engineering design at a high frequency: *identifying constraints, developing solutions*, and *testing and evaluating*.

Monty used these three aspects of engineering design when describing the engineering design process shown in her concept map:

> You have a solution, or like a potential solution. So basically an idea that you come up with. And then from there you do further research for what materials you need, the time it would take to make it and then how to do it. And then so from there the time, materials, and research all come into a trial, and then you have either error or success, and if you have an error, then you go back up to the failed attempt section where it's what went wrong, and then if you have success, you're

> thinking about how it could be better and how you can teach it so that it's like a sustainable idea. And then so with how it could be better, you would repeat the entire process starting with whatever problem you have with it. (Monty, Winter Interview)

This participant understood the need to develop solutions and test them—in line with the basic *NGSS* description—and also discussed the need to identify constraints that an engineer must work within throughout the process. This aspect is a slightly more complex part of the *NGSS* description of engineering design, which does not appear in the grade band standards until grade 3 (NGSS Lead States, 2013).

Xandra discussed the most (eight) aspects of engineering design at a high frequency: *identifying constraints, problem or need, thinking about the user, developing solutions, testing and evaluating, based on science, collaboration,* and *using technology*. Several of these aspects are also in line with the *NGSS* description of engineering design (*problem or need, identifying constraints, developing solutions,* and *testing and evaluating*), however, some indicate a more sophisticated understanding. Xandra recognized the need to use science and technology throughout the engineering design process and also viewed collaboration and the sharing of knowledge and experience as important. She further understood the importance of thinking about the user when designing solutions, an important aspect of engineering in the business world.

Medium frequency. I considered aspects of engineering design that were discussed between 10 and 20 times medium in frequency. There were far more participants who discussed aspects of engineering design at this frequency compared to those who discussed aspects at a high frequency. Carlos was the only participant who discussed one aspect at this frequency level: *research problem*. He was one of only three participants who discussed this aspect of engineering design at a medium or high frequency, indicating that most participants did not view this aspect as an important part of engineering design.

Some participants only discussed two aspects of engineering design at a medium frequency: Kristy, *communication* and *physical object*; Molly, *identifying constraints* and *developing solutions*; and Saul, *design process* and *physical object*. Kristy's use of these aspects of engineering design indicates that her view included the need to construct a model or prototype design, usually by creating a physical object. This is evident in her description of this part of the engineering design process:

> So you have an idea, and it has a design, and you make a mockup of it; you kind of try to make it….So then you have your prototype, and then from your prototype is when you make your final. And kind of work out all the bugs, and you make your equivocal final product; your real presentation; your finished, polished item. (Kristy, Focus Group)

Saul also discussed the need to create a physical object through engineering design, but also recognized the importance of the iterative process by which things move from abstract ideas to concrete objects. Molly, on the other hand, discussed aspects that are part of the beginning of the *NGSS* description of engineering design—identifying constraints to work within and developing solutions for the engineering problem.

Several participants discussed three or four aspects of engineering design at a medium frequency. More specifically, one participant, Kari, discussed three aspects of engineering design at a medium frequency: *communication, developing solutions*, and *physical object*. Several others discussed four aspects: Anthony, *problem or need, developing solutions, design process,* and *physical object*; Caitlyn, *identifying constraints, problem or need, developing solutions,* and *testing and evaluating*; David, *identifying constraints, problem or need, communication*, and design process; and Kayla, *identifying constraints, developing solutions, design process,* and *based on science*. A majority of these aspects of engineering design are in line with those described in the *NGSS* and help to define the process of engineering design in basic terms. Other aspects, however, imply that participants viewed engineering as the creation of a physical object—whether it be a physical prototype of a design (communicating design visually or physically) or a finished product. Lastly, Kayla's use of the aspect, *based on science*, indicated that she viewed science as a critical aspect of engineering, which only two other participants discussed at a medium or high frequency.

Several participants discussed five aspects of engineering design at a medium frequency: Haylee, *problem or need, developing solutions, design process, testing and evaluating,* and *physical object*; Nick, *communication, developing solutions, design process, testing and evaluating,* and *physical object*; Ralph, *problem or need, thinking about the user, developing solutions, secondary effects*, and *design process*; Rick, *identifying constraints, problem or need, creativity, inspiration*, and *physical object*; Sasha, *identifying constraints, problem or need, design process, testing and evaluating*, and *physical object*; and Xandra, *research problem, communication, research solutions, optimal design*, and *design process*. While many of the aspects of engineering design discussed by these participants are part of the description provided in the *NGSS* (*problem or need, identifying constraints, developing solutions, testing and evaluating, design process*, and *optimal design*), there are some that indicate a different perspective of engineering design.

Many participants also held the view that engineering design must result in the creation of a physical object, occasionally a prototype or other physical means of communicating a design. Ralph, Rick, and Xandra discussed more unique aspects of engineering design, however. Ralph's unique aspects (*thinking about the user* and *secondary effects*) demonstrated his view of engineering as a human endeavor where the engineer must consider the potential user and the potential effects on humanity as a result of use of the engineered solution. He described these considerations of engineering design when discussing what he had learned from an engineering class he took:

> There's this ethics class I took…and it's teaching us about the—not just, like, how to design but how to—what to take into account when you're designing. So, you have to take into account everybody who could be affected by it. And the actual repercussions of certain designs, even if the design is made for good reasons, [it] could turn out bad. (Ralph, Winter Interview)

Table 4d

Frequency of Participant Discussion by Aspect of Engineering Design

Aspect of Engineering Design	Participant								
	Adam	Anth-ony	Caitlyn	Carlos	Dana	David	Haylee	Jas-mine	Josh
Identifying constraints	6	6	16	9	4	12	10	8	2
Problem or need	26	18	19	31	7	16	16	9	4
Research Problem	1			12	1	3		1	
The scope of design				2		1	1		
Subproblems	1	4		3	1		2		
Thinking about the user	1		1	1	1	3	2		
Communication	15	7	7	10	6	13	9		3
Research Solutions	1		1	2	1	7	1		
Developing solutions	20	14	16	34	5	24	11	3	
Secondary effects		1					1		1
Comparing solutions	2	2	2	1	2	8	4		
Optimal design	4	2	4	9	2	8	4	1	1
Design Process	18	11	9	25	8	12	15	8	2
Testing and evaluating	20	9	16	22	4	10	12	6	1
Competition	1		1			2	1		
Aesthetics			1		5				3
Creativity	2	2	1	5	2	3			1
Prior knowledge and experience	1		3			1	1	1	1
Based on Science	13		5	3	5	9	7	5	3
Simplicity	1			2			1		1
Collaboration	3	1		2			3		
Evolutionary design	1	1				2			
Final product	1	4	4	10	7	1	4	1	1
Never ending process		3	2	1	2	5			1
Engineering is Integrated				1	2		1		1
Inspiration		2							
Physical Object	11	12	10	28	9	8	17	5	4
Thinking like an Engineer				2		1			
Using mathematics		1	2		3		5		1
Using Technology	5	3	4	7	9	2	2	1	4

Table 4d cont.

Frequency of Participant Discussion by Aspect of Engineering Design

Aspect of Engineering Design	Participant								
	Kari	Kayla	Ken	Kristy	Kurt	Macy	Molly	Monty	Nick
Identifying constraints	5	16	4	8	4	8	13	34	4
Problem or need	9	22	6	3	3	4	10	19	21
Research Problem	1	2		1		4	3	12	3
The scope of design		1		1				2	
Subproblems	1		2		2	2	1	1	3
Thinking about the user	6	2			2	1		9	2
Communication	14	2	1	14	1	1	7	16	15
Research Solutions	6	4		1		3	2	14	1
Developing solutions	17	20		3	2	5	12	22	19
Secondary effects	2	1						1	1
Comparing solutions	1	2		2		2	2	9	3
Optimal design	5	9	3	2	2	1	2	14	3
Design Process	9	13	9	9	4	4	8	17	14
Testing and evaluating	10	21	3	6	3	3	7	23	14
Competition				1					
Aesthetics			3	4	3			7	
Creativity	4	1	2	1	1	3	3	20	
Prior knowledge and experience	1	3		1		2		5	
Based on Science	5	11	5	2	3	8	5	4	8
Simplicity		1	1						
Collaboration	10	2		3		2	4	5	1
Evolutionary design		3			1		3	2	1
Final product	4	4	2	4	4		2	1	1
Never ending process			1		1			5	3
Engineering is Integrated			2		1				7
Inspiration	0		1	5			1	7	4
Physical Object	13	10	2	12	3	3	7	10	18
Thinking like an Engineer						1		2	2
Using mathematics		2	2	5	1	4			2
Using Technology	1	3	3	8	3	1		2	6

Table 4d cont.

Frequency of Participant Discussion by Aspect of Engineering Design

Aspect of Engineering Design	**Participant**								
	Patty	Ralph	Rick	Sally	Sandra	Sasha	Saul	Xandra	Zeb
Identifying constraints	2	9	17	4	8	16	7	29	12
Problem or need	7	17	12	10	4	11	25	37	20
Research Problem		8		1	4	4	6	13	2
The scope of design						1		4	1
Subproblems		1	2		2	1	4	6	8
Thinking about the user		15	3		1	5	1	25	1
Communication	1	6	3		1	8	2	15	17
Research Solutions	1	3			3	4	6	11	6
Developing solutions	4	15	5	6	5	13	22	21	20
Secondary effects		14				1		2	
Comparing solutions		10	1		2	3	4	6	8
Optimal design		6	2		1	2	9	13	10
Design Process	3	11	7	5	4	11	11	14	16
Testing and evaluating	2	10	6	3	3	11	9	29	19
Competition		3					3	3	7
Aesthetics		1						5	
Creativity		4	13		3	3	7	5	5
Prior knowledge and experience		2	2	1	2	1	1	7	2
Based on Science	4	9	5	8	8	10	2	22	6
Simplicity		1	2				3		6
Collaboration	2		5	1	2	8	1	22	10
Evolutionary design			1			1		8	7
Final product	1		1	1		2	7	4	6
Never ending process		5		1		1	1	2	1
Engineering is Integrated		6	6					6	
Inspiration		1	14			1	1		12
Physical Object	7	5	18	6	3	13	18	9	29
Thinking like an Engineer		1	8		1	1		5	8
Using mathematics		7	9		4	4	1	5	1
Using Technology	1	8	5	1	1	8	4	26	19

Rick’s unique aspects (*creativity,* and *inspiration*) demonstrated his view of engineering as a creative endeavor that involves an element of inspiration when the engineer can spontaneously come up with an interesting solution. Xandra’s unique aspects (*research problem* and *research solutions*) reflected her view of engineering design as being based on research—whether it be about the context of the problem, including the science behind it, or researching what has already been done to help inform one’s solutions and design. She described how one should research the problem before generating potential solutions, for example, by “learn[ing] the limitations of your materials”. She also discussed how it is smart to research solutions ahead of generating one’s own as well: “So to find a solution… always read up on some literature. It's like, if you want to come up with a solution, someone else already came up with a solution, so you can just apply the solution” (Xandra, Post-Summer Interview).

Three participants discussed more than five aspects of engineering design at a medium frequency: Adam, *communication, developing solutions, design process, testing and evaluating, based on science*, and *physical object*; Monty, *problem or need, research problem, communication, research solutions, optimal design*, and *creativity*, and Zeb, *identifying constraints, problem or need, communication, developing solutions, optimal design, design process, testing and evaluating*, and *inspiration*. Again, many of these are aspects of the *NGSS* description of engineering design or represent the relatively common view of engineering as creating a physical object or prototype. Some of these aspects represent participant’s specific view of engineering design as either *based on science* (Adam), *research based* and *creative* (Monty), or *based on inspired ideas* (Zeb). Overall, these participants discussed many aspects of engineering design at a relatively high frequency, indicating that all three of them had a broad understanding of engineering design.

Low frequency. Aspects of engineering design that were discussed less than 10 times were considered low frequency All participants discussed multiple aspects of engineering design at this frequency, but some participants *only* discussed aspects at a low frequency and did not discuss any aspects at a high or medium frequency. This might be a factor of these participants not being involved in as many instances of data collection compared to the others (which was the case. The following participants discussed a varying amount of aspects of engineering design (ranging from 12 to 21), but all of these occurrences were considered low frequency: Dana, 21 aspects; Jasmine, 12 aspects; Josh,18 aspects; Ken, 18 aspects; Kurt, 19 aspects; Macy, 20 aspects; Patty, 12 aspects; Sally, 13 aspects; and Sandra, 20 aspects.

Some aspects of engineering design were only discussed at a low frequency by all participants: *the scope of design*, 9 participants; *subproblems*, 19 participants; *comparing solutions*, 21 participants; *competition*, 9 participants; *aesthetics*, 9 participants; *prior knowledge and experience*, 19 participants; *simplicity*, 10 participants; *evolutionary design*, 12 participants; *final product*, 24 participants; *never ending process*, 16 participants; *engineering is integrated*, 10 participants; *inspiration*, 12 participants; *thinking like an engineer*, 11 participants; *using mathematics*, 18 participants. This might indicate that participants overall were unaware of or were not confident about the role that these aspects play in the engineering design process. Most of these aspects of engineering design are not present in the *Next Generation Science Standards* (NGSS Lead States, 2013) and were added either through the review of literature on engineering design (see Chapter 2 for more information) or during coding as they emerged in participants' discussion.

Level 2 Findings: Conceptual Categories of Engineering Design

After I completed level 1 analyses, I began my level 2 analyses by identifying which of the 30 aspects of engineering design discussed above could be combined into larger conceptual categories of engineering design (see Table 4e). This was done by iteratively looking across the data to identify aspects of engineering design that were commonly discussed together by a participant at a given instance (a single interview and the associated concept map, if applicable). Through this process, six conceptual categories of engineering design emerged as distinct conceptions that participants held. Of these six, one category—*Basic NGSS*—was articulated by all participants in all instances in the data. As such, I only briefly discuss the *Basic NGSS* category as a distinct conceptual category in these findings. I more thoroughly discuss the other five categories because of the potential impact they might have on participants' understanding and conceptions of engineering design.

More specifically, participants were classified into a conceptual category if they discussed a simple majority (e.g., 3 out of 4, 3 out of 5, or 4 out of 7) of the aspects of engineering design that are part of that category. Participants could be classified into multiple conceptual categories if they discussed a substantial number of aspects of engineering design that fell into multiple categories – if they discussed a simple majority of aspects in multiple categories simultaneously (i.e., in a single instance in the data).

Below, I first present the overall findings related to these six identified conceptual categories, including participants and particular instances that were classified into each. Next, findings related to combinations of two, three, and four conceptual categories are presented by participant and particular instance. Finally, I examine the few participants' descriptions of engineering design that could be considered the most complex or integrated.

Overall Findings: Conceptual Categories

Six conceptual categories for engineering design emerged through level 2 analyses: *Basic NGSS, Business or Product Focused, Knowledge and Skills, Creative Thinking, Human Centered,* and *Improvement.* Table 4e below lists each conceptual category, the criteria for inclusion in each, and the specific instances a participant was included in that conceptual category. Because all participants identified aspects of engineering design that were in line with the basic description provided in the *Next Generation Science Standards* (NGSS Lead States, 2013), they were all included in the *Basic NGSS* category. This indicates that all participants across the data had at least a baseline understanding of engineering design that was aligned with the basic *NGSS* description. Because of this, the *Basic NGSS* category is not discussed in-depth in this level of findings and is not added in a participants' total number of classified conceptual categories (discussed further below).

Table 4e

Conceptual Categories of Engineering Design

Conceptual Category	Criteria for Inclusion	Description	Participants Included	Instance Included (only this category)
Basic NGSS	Inclusion in this category requires that participants discuss at least 3 of the following aspects of engineering design: 1) Define a problem or need 2) Identify constraints 3) Develop solutions 4) Optimizing the solution 5) The iterative design process	This category includes references to the aspects of engineering design that are included in the basic description of engineering design provided in the *Next Generation Science Standards.*	Anthony	Initial Interview
			Caitlyn	Winter Interview
			Molly	Initial Interview
				Winter Interview
			Patty	Focus Group
			Ralph	Post-Summer Interview*
Business or Product Focused	Inclusion in this category requires that participants discuss at least 4 of the following aspects of engineering design: 1) Identifying constraints 2) The scope of design 3) Subproblems 4) Competition 5) Simplicity 6) Final product 7) Physical object	This category relates to a business or product focused view of engineering design because they highlight the importance of working within the constraints and scope of the engineering project-at-hand and breaking down the project into smaller, more manageable goals. There is also a focus on creating a physical object or final product that is the simplest or most efficient and is better than the competition's.	Carlos	Winter Interview
				Final Interview
			Kayla	Initial Interview
			Saul	Initial Interview
				Winter Interview
				Final Interview

Knowledge & Skills	Inclusion in this category requires that participants discuss at least 4 of the following aspects of engineering design: 1) Research the problem 2) Research solutions 3) Prior knowledge and experience 4) Based on science 5) Engineering is integrated 6) Using mathematics 7) Using technology	This category relates to using one's knowledge and skills in engineering design because they highlight how one needs to utilize prior knowledge and skills (from various areas including science, mathematics, technology, or other subject) or seek more knowledge and skill (usually through research) through the engineering design process.	Carlos Jasmine Nick Rick Sally	Initial Interview Focus Group Initial Interview Final Interview Focus Group
Creative Thinking	Inclusion in this category requires that participants discuss at least 3 of the following aspects of engineering design: 1) Aesthetics 2) Creativity 3) Inspiration 4) Thinking like an engineer	This category relates to thinking in a way that allows one to solve problems creatively by generating innovative ideas that draw on one's creative and artistic skills.	None	None
Human Centered	Inclusion in this category requires that participants discuss at least 3 of the following aspects of engineering design: 1) Thinking about the user 2) Communication 3) Secondary effects 4) Collaboration	This category of engineering design highlights the human element of engineering design, which includes the need to think about how the design process involves working with and communicating with others and how the product should consider people (either through personal use or as an effect of others' use).	Kari Sasha	Winter Interview Winter Interview

Improvement	Inclusion in this category requires that participants discuss at least 3 of the following aspects of engineering design: 1) Comparing solutions 2) Optimal design 3) Testing and evaluation 4) Evolutionary design 5) Never ending process	This category of engineering design highlight the desire to improve engineering solutions through constantly testing, comparing and evaluating them.	Adam	Initial Interview
				Winter Interview
			Anthony	Winter Interview
				Final Interview
			Caitlyn	Final Interview
			David	Final Interview
			Kayla	Winter Interview
			Molly	Final Interview
			Ralph	Final Interview
			Nick	Post-Summer Interview
				Final Interview

*Ralph did not have a post-summer interview, therefore the data from this instance only consists of his concept map. This limited data for this instance might have affected the conceptual category that he was placed into.

Basic NGSS. All participants across all instances in the data identified a substantial number of aspects of engineering design that could be classified into the *Basic NGSS* category, but the vast majority of these instances were also classified into other conceptual categories as well. Indeed, five participants across six separate instances identified at least three of the five (a simple majority) aspects of engineering design that could only be classified into the *Basic NGSS* category, without simultaneously being classified into at least one additional conceptual category (see Table 4e below). Because of this, the *Basic NGSS* category was not factored into the classification of participants into conceptual categories from this point forward. This category was included to highlight that some participants in a handful of instances did not indicate a more complex view of engineering design beyond just the *Basic NGSS* conceptual category.

Business or product focused. Three participants in six separate instances in the data (see Table 4e below) identified at least four of the seven (a simple majority) aspects of engineering design to be classified into only the *Business or Product Focused* conceptual category, without simultaneously being classified into at least one additional conceptual category (excluding *Basic NGSS*). Two participants were classified into this category at multiple instances in data collection: Carlos and Saul. They held this view of engineering design—as business or product focused—at multiple times throughout the academic year. In describing how he might teach engineering design to high school students, Saul demonstrated this business-focused mindset of engineering in saying the following:

> The hard part is teaching them other stuff. Like, "Oh okay, I know what the ideal is." Or "I know what I, after going through all the processes, I know the next best thing for what I'm capable of doing is. How do I do it then?"…Know what perfection is or knowing what the ideal is and treat it as your competition and try to be as close to that as possible, and you'll be successful….I would probably just give examples of that. Probably mention Elon [Musk]. Like, successful products out there like Google. Why is Google better than Bing? You know, and all that stuff. (Initial Interview)

It was quite common for participants to be included in the *Business or Product Focused* category in addition to at least one other conceptual category of engineering design. Seventeen participants in 25 instances throughout the data discussed at least four aspects of engineering design from the *Business or Product Focused* conceptual category along with a substantial number of aspects to classify them in at least one other conceptual category. Participants who discussed aspects from more than one conceptual category were thought to have a more complex understanding of engineering design; this is discussed further below.

Knowledge and skills. Five participants in five separate instances in the data (see Table 4e below) identified at least four of the seven (a simple majority) aspects of engineering design to be classified into only the *Knowledge and Skills* conceptual category, without simultaneously being classified into at least one additional conceptual category (excluding *Basic NGSS*). Preservice teacher, David, described how one must use their knowledge in engineering design:

> There's a lot going on between problem and original concept. In that space, there's so much happening. Whether it's stuff you already learned – like your own fund of knowledge. Something breaks and you're like, "Oh, I can fix that." You've had a whole lifetime to see things that might bring you to an original concept. But there's also just research you can do, whether that's seeing what other solutions have been done in the past, how the science affects that, what tools you have available…so much goes into this first original concept that's hard to get to. (Winter Interview)

Of participants who were interviewed and completed concept maps at multiple instances throughout the study, none were classified into only this category more than once. This might indicate that while sometimes this conceptual category fit well with a participant's view or understanding of engineering design, in other instances, it might have been combined with other categories to create a more complex view or understanding, or a participant's view of engineering might have moved away from this view and towards another conceptual category instead. Indeed, 20 participants in 27 instances identified a substantial number of aspects of engineering design from the *Knowledge and Skills* category in addition to those from at least one other category.

Creative thinking. This conceptual category was discussed by participants substantially less than any other category. There were no participants who identified *only* the necessary three aspects of engineering design to include them in the *Creative Thinking* category without also identifying a substantial number of aspects to classify them into at least one other conceptual category. Further, there were only 14 instances where participants discussed this conceptual category (of a possible 70 instances). This might indicate that, while some participants recognized creative thinking as a significant feature of engineering design, they did not think this is the only important feature, and thus, they included other conceptual categories as well. For example, Monty discussed this conceptual category in her initial interview but was also classified into two other conceptual categories. She talked about the creative and innovative aspects of engineering design when asked what she thinks engineering is:

> I think it is innovation. I think engineering is coming up with an idea and creating it out of, you know, like knowledge you've had before or resources you've had before. Something like that. It involves a lot of critical thinking and being original. (Initial Interview)

To clarify, while no participant in a single instance in the data (see Table 4e below) identified at least three of the four (a simple majority) aspects of engineering design to be classified into *only* the *Creative Thinking* conceptual category, many were simultaneously classified into at least one additional conceptual category (excluding *Basic NGSS*). As such, I included the *Creative Thinking* as a distinct conceptual category because the aspects of engineering design included in it—aesthetics, creativity, inspiration, and thinking like an engineer—do not fit well within any of the other conceptual categories. I argue that this category, when discussed in concert with other categories, provides a more robust interpretation of the participants' views or understandings of engineering design.

Human centered. Two participants across two separate instances in the data (see Table 4e below) identified at least three of the four (a simple majority) aspects of engineering design to be classified into only the *Human Centered* conceptual category, without simultaneously being classified into at least one additional conceptual category (excluding *Basic NGSS*). One of these participants, Kari, discussed how these human centered aspects of engineering design were often missing from the engineering-focused projects her students did:

> They didn't analyze [their solution] or interpret how that would affect the area. They didn't really get any critique from other groups or identify possible problems to their design. They kind of just communicated the results. So there's no correction process in there of like, "Is this actually feasibly going to work? And if not, how can we make this better? What's a realistic solution?" I got a lot of projects that were like, "Okay yeah, maybe, but how do you plan on doing that? That's not something that we can actually do in the real world." I didn't tell them this, but things like, "Yeah, let's make like a crosswalk for deer and

> mountain lions." I'm like, "Okay, but how do you suppose they are going to push the button, let's say—," or simple things like that. (Final Interview)

Because there were few participants (out of the possible 27) and even fewer instances (out of the possible 70) that were classified into this conceptual category, this view of engineering design alone was not commonly held by participants across the data. However, this conceptual category, when discussed in concert with others, was more common throughout the data (discussed further below). Eleven participants across 19 instances discussed a substantial number of aspects of engineering design to classify them in the *Human Centered* conceptual category in addition to at least one other conceptual category.

Improvement. Eight participants across 11 separate instances in the data (see Table 4e below) identified at least three of the five (a simple majority) aspects of engineering design to be classified into only the *Improvement* conceptual category, without simultaneously being classified into at least one additional conceptual category (excluding *Basic NGSS*). David described his view of engineering design as being about constant improvement:

> The goal of engineering in general [is] just making something better. Then even after you've done the application [of your solution], you're like "All right, how can you make it even better again and again?" So that never ends. Getting there is kind of this looping practice, but that also never really ends in a solution, but a whole bunch of things. (Final Interview)

While some participants—Caitlyn, David, Kayla, Molly, and Ralph—were only classified into this conceptual category in a single instance, three other participants were classified into this category twice throughout the data. In other words, while some participants' descriptions of engineering design moved away from this category (or added more categories to create a more complex understanding or view), others maintained this category over time. Twenty-six participants across 33 instances discussed a substantial number of aspects of engineering design to classify them in the *Improvement* category in addition to at least one other conceptual category of engineering design.

Overall Findings: Multiple Conceptual Categories

I found that participants sometimes discussed two, three, four, or all of the above conceptual categories together (not including Basic NGSS). In doing so, these participants constructed new, more complex understandings of engineering design. I identified nine higher-level combinations of two major conceptual categories, five even more complex combinations of three major conceptual categories, three very complex combinations of four major conceptual categories, and finally, what an integrated understanding of engineering design looked like from the data, which was a combination of all the major conceptual categories.

Below, each of these combinations of conceptual categories observed in the data is described. Participants were mapped to the combinations that they fit within (Table 4f). As the number of conceptual categories in which a participant's discussion of engineering design fit within increased, it was theorized that the participant conveyed a more complex understanding of the many facets of engineering design at that instance in the data (see

Figure 4a). How the six conceptual categories inform each of these more complex combinations will be explained in detail below.

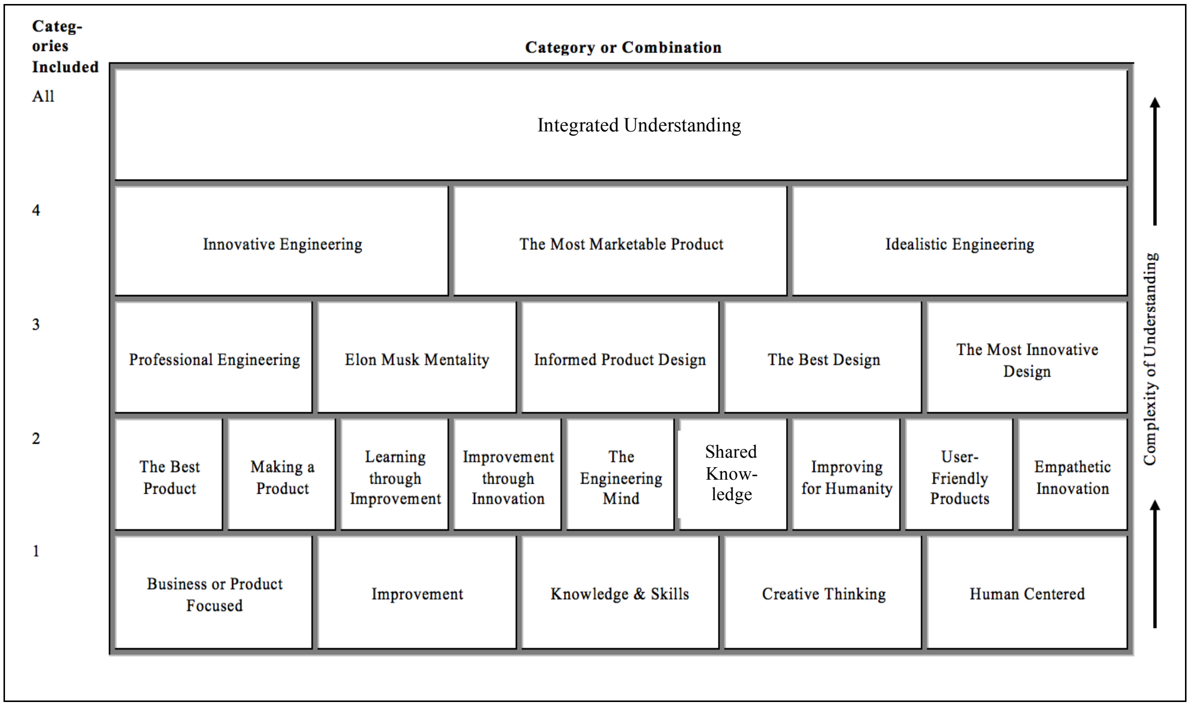


Figure 4a. Levels of conceptual categories by complexity of understanding of engineering design

Combining two conceptual categories. Seven participants' descriptions of engineering design could be classified into two conceptual categories simultaneously in nine instances in the data. These participants conveyed a more complex understanding of engineering design at these points in time than those whose descriptions were only classified into a single category. I identified nine possible combinations of two conceptual categories in the data (Figure 4b). A description of each combination and the relevant participants is given below.

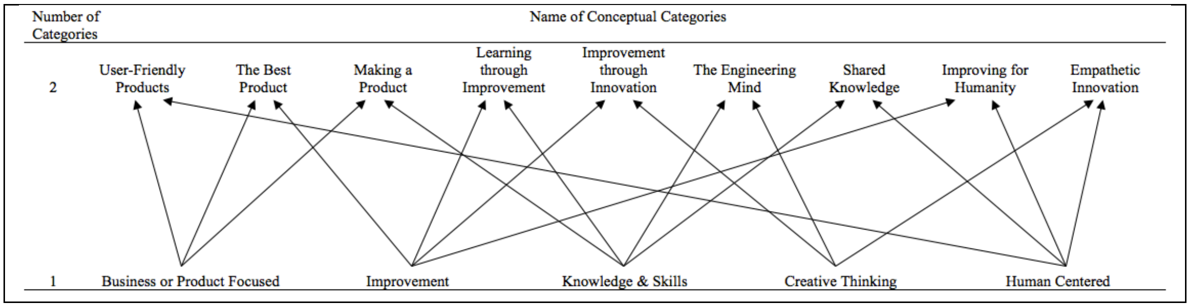


Figure 4b. Combinations of two conceptual categories of engineering design

The best product. The combination of the *Business or Product Focused* conceptual category and the *Improvement* category yielded a description that incorporated the processes engineers use to create the best possible product within the constraints of the business world. While only two participants at two instances—Haylee and Anthony near the beginning of the academic year—discussed aspects of engineering design that included only these two conceptual categories, many other instances included these two categories and at least one more category and conveyed an even more complex understanding of engineering design grounded in this construct.

Making a product. This combination of the *Business or Product Focused* conceptual category and the *Knowledge and Skills* category conveyed an understanding of the need for an engineer in a business or product oriented setting to have the requisite knowledge and skills to create an adequate product. If they do not, they recognize that engineers must utilize research as a method to learn the necessary knowledge and/or skills to execute their design. Only one participant in a single instance—Adam in his final interview—described engineering design in ways aligned with these two conceptual categories, however, many instances included these in addition to at least one other category.

Learning through improvement. This combination of the *Knowledge and Skills* and *Improvement* conceptual categories conveyed an understanding of how engineers can use their knowledge and skills to create designs, and that through making iterative improvement to those designs, engineers can apply and/or learn further knowledge and skills through the process. This indicated an understanding of the learning that can occur during the iterative process of optimization in engineering design. Three participants at three instances—David, Kayla, and Saul near the beginning of the academic year—were classified into these two conceptual categories, however, there were several other instances where participants' discussion included these categories in addition to at least one other category as well.

Improvement through innovation. The combination of the *Improvement* and *Creative Thinking* conceptual categories conveyed an understanding of the need for creative and innovative thinking in order to improve engineering designs. While the name may sound similar to the above combination, this conception of engineering design recognizes that a good design requires elements of creativity that make it better than other designs either through elements like aesthetics, or because, through creative thinking, the engineer was able to develop a novel solution to solve an otherwise unsolvable problem. While only one participant at one instance—Monty in her initial interview—was classified into these two conceptual categories, other instances included these categories in addition to at least one other.

The engineering mind. The combination of the *Creative Thinking* and *Knowledge and Skills* conceptual categories suggested an understanding of how an engineer has a particular type of mind, which seeks out and uses knowledge and skills across multiple areas (science, math, technology, etc.) and uses them creatively to develop innovative designs. This conception focuses on the way engineers think over what they do. Only one participant in one instance—Rick in his winter interview—was classified in both of these conceptual categories, however, there were several other instances which included these in addition to at least one other category.

Shared knowledge. The combination of the *Knowledge and Skills* and the *Human Centered* conceptual categories conveyed a fairly basic view of engineering design that does not take into consideration the process by which problems are actually solved. Instead, this combination focuses on engineering as a knowledge and skills based endeavor, which centers around the need for and collaboration among people to develop solutions. Only one participant at one instance—Kari in her final interview—discussed the engineering design aspects to classify her into these two conceptual categories, however, many instances included these categories in addition to at least one more category, which indicated a more integrated understanding.

Improving for humanity. The combination of the *Improvement* and *Human Centered* conceptual categories also conveyed a fairly basic view of engineering design that does not take into consideration the process by which problems are actually solved or whether the process results in a product or object that can be used. This combination did, however, demonstrate a view of engineering that involves creating the best solutions to a problem or need for humans, by humans. Only one participant at one instance—Kari in her initial interview—discussed the aspects of engineering design to classify her into these two conceptual categories, however, many other instances include these two in addition to at least one other category.

User-friendly products. The combination of the *Business or Product Focused* and the *Human Centered* conceptual categories demonstrated a view of engineering as the development of a product that meets the demands and considerations of the users of that product. Above all, this view recognized that to create a product that will sell, one must take into consideration what the consumers want. Only one participant at one instance—Nick in his winter interview—discussed the aspects of engineering design needed to classify him into these two conceptual categories, however, many other instances mentioned these in addition to at least one other category.

Empathetic innovation. The combination of the *Creative Thinking* and the *Human Centered* conceptual categories of engineering design presented a view of engineering that centers around the internal factors of the people involved in the engineering design process: users and engineers. While the combination above has a product orientation, this view focused on the human element of engineering, including the creative, innovative thinking that engineers need, and the need to empathize with potential users and collaborate throughout the engineering design process. Only one participant at one instance—Rick in his initial interview—discussed the aspects of engineering design needed to classify him into these two conceptual categories, however, many other instances included these in addition to at least one other category.

Combining three conceptual categories. Fifteen participants' descriptions of engineering design fell into three conceptual categories simultaneously at 17 instances in the data. These participants conveyed a more complex understanding of engineering design at those points in time than those whose descriptions were only classified into a single category or into two categories. Five possible combinations of three conceptual categories were identified in the data (Figure 4c).

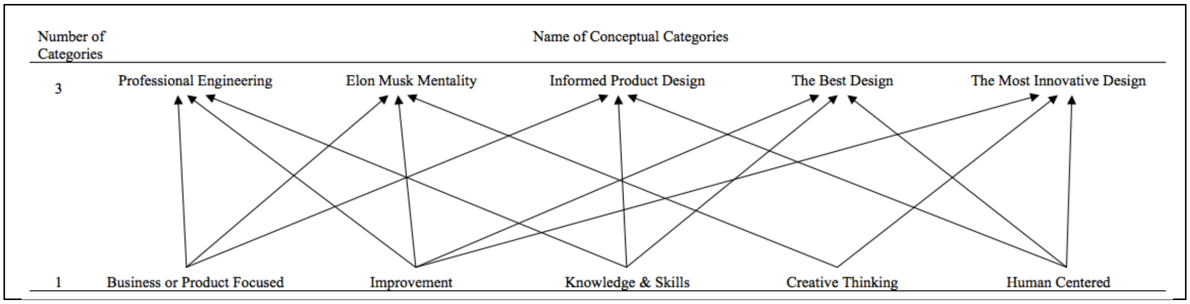


Figure 4c. Combinations of three conceptual categories of engineering design

Professional engineering. This combination of conceptual categories for engineering design included *Business or Product Focused, Improvement*, and *Knowledge and Skills* categories. The combination of these three conceptual categories yielded a fairly complex description of engineering design in the professional realm. An individual who conveyed this conception of engineering design recognized the need to make a product using one's knowledge and skills (as an engineer) that will sell better than the competition's. Preservice teacher, Sasha, used many aspects of engineering design from these three conceptual categories in her description of the engineering design process:

> So, it kind of starts with defining a problem and doing research and they kind of work together. Your research informs how you define a problem. And I guess research can include market evaluation, and problems related to standards. Like this trade-off so if you can't do everything you have to prioritize stuff. And then you go to brainstorming, once you have your problem, and then you are designing

> which could include physics or, I guess, really any science. And then you make a prototype, like physical or in a computer or something. And you test it, collect some data to see if you have met your standards. And I guess seeing if you met the standards is the evaluation. Usually you need to revise it and keep going through that sort of a loop until you have met your standards. And then you kind of (decide) if you have solved your problem, except the thing is you can always make it better. So, you can solve it in a sense, like you can sell it or something, but you can always make it better and keep going through that loop. (Initial Interview).

This description is more complex than *The Best Product* combination above because it recognizes the knowledge and skills that engineers must learn, possess, and use in a professional setting to create the best products. Six participants across six instances discussed enough aspects of engineering design to classify them into all three conceptual categories: *Business or Product Focused, Improvement*, and *Knowledge and Skills.* Some participants in some instances were also classified in these same three categories in addition to at least one more, discussed below.

Elon Musk mentality. The combination of the three conceptual categories *Business or Product Focused, Improvement*, and *Creative Thinking* conveyed how the most creative engineers can leverage their knowledge and skills in the business world to develop innovative and novel solutions to engineering problems. This construct described engineers like Elon Musk, who has developed some of the best, most creative, and most innovative solutions in engineering, even if it does not align with their personal background or education. Two participants—Rick and Zeb—across four instances (Zeb fell within these three categories in three of his four interviews) described this particular combination of conceptual categories for engineering design, although some other instances included these three categories in addition to at least one other.

Zeb's description of his concept map of engineering design included many of the aspects of engineering design that make up these three conceptual categories:

> Engineering problems require engineered solutions, which starts with brainstorming and results in numerous possibilities, which you should study critically or with skepticism. And you should narrow it down to one idea or design and refine it… On this section of the concept map is where you would test and prototype whatever you built in your design, which is the skepticism that you give to your numerous possibilities, and then results are used to inform design. So maybe the geometry is not as well as it could have been laid out. But yeah, I think the idea is slowly refining your ideas iteratively, and your designs. Kind of controlling your creativity and making it into one thing. And make a prototype, test it, build an apparatus if you need to, and then, you know, make a Mach II of it and learn by doing that. Make one design and then self-critique, and say, "What can I do better? What worked here? What didn't work?" Kind of be self-reflective and self-critical in a way that it's constructive, and then implement that in the next round. So, I think my concepts are related in that it's just… it's being curious in a controlled way, and defining your problems, and building your thing, and iteratively refining its design. (Post-summer Interview)

In this extended quote, Zeb highlighted the need to build a physical product or solution by “controlling your creativity” and iteratively refining and improving. Because Zeb held this view of engineering so consistently over his interviews throughout the study, this might be his predominant view of engineering design.

Informed product design. The combination of the *Knowledge and Skills, Business or Product Focused,* and *Human Centered* conceptual categories conveyed a fairly sophisticated understanding of professional engineering that creates products for people. This view recognized the need for an engineer to use knowledge and skills, in addition to taking into account considerations for business and the potential user to create a product that will sell well. Two participants across two instances—Haylee at the end of the academic year and Xandra near the beginning of the academic year—discussed enough aspects of engineering design to be classified in all three of these conceptual categories.

Xandra described the complexities of engineering design as they relate to the combination of these three conceptual categories:

> Troubleshooting in engineering… you're on a very specific timeline, for like, “okay this needs to be done by”, like “we need to have constructed it by then, by this date, we need to be troubleshooting it by this date. Then refining it by this date”… I think that's something I need help to do engineering, to teach myself like I said, the timeline of-- because then you introduce the human element of “okay this update for this app needs to go out by this date”. Because there could be economic ramifications for a specific company… You could just be messing around with it and then you realize that… "Oh this works better in this way" or

> "Oh I can..." you know "...this autonomous robot responds better in these types of environments". That's also tinkering. With tinkering it is not just hands on things, it's also observing how technology works better. (Initial Interview).

While this view is fairly complex, there were other instances which were identified that included at least one other conceptual category in addition to these three.

The best design. The combination of the *Improvement, Knowledge and Skills,* and *Human Centered* conceptual categories conveyed a fairly complex understanding of engineering design and the various inputs that go into creating the best possible design. The best design can only be created when an engineer uses knowledge, skills, and information about the user and usually works with others to gain the advantage of multiple perspectives. Four participants—Macy, Ralph, Sandra, and Sasha—across four different instances identified enough aspects of engineering design to be classified into all three of these conceptual categories.

Ralph focused heavily on the human centered nature of engineering design and the need to research and use one's knowledge to create better designs for the user:

> I guess the most important [part of engineering design] would be accessibility. Because in general, many things can be made, but can it be made [so] that people will want to use them, or will be able to use them? … Can people who don't have experience with engineering actually use it? Is it better than anything else that there is already out there, or why is it, why would this be used over anything else? Who can use it and is it affordable to those that [are in] the target audience… Could [the product or solution] inspire in the future? Even though at that stage, it's

> not necessarily the best, in the future they might be able to make it better. (Initial Interview)

Some instances included these categories of engineering design in addition to at least one other category to conveyed an even more integrated understanding of engineering design.

The most innovative design. The combination of the *Improvement, Creative Thinking,* and *Human Centered* conceptual categories conveyed an idealistic view of engineering design where the engineer is able to constantly strive for the best possible design that is developed through creative and innovative thinking, and that takes into consideration those who may benefit from this design. While this is similar to the combination above, this conception of engineering acknowledges the need to use creative thinking. This view is idealistic because it is not constrained by time, money, or the need to create a final product. Only one participant at one instance—Monty in her final interview—discussed aspects of engineering design to be classified in these three conceptual categories. She demonstrated this view when describing the engineering design process:

> I think that there's always room for improvement… [and] I think that [the] marketing and aesthetic part is really important because if you're designing some sort of new product, and it's really cool, but it's not something that anyone wants to buy, then it's kind of useless. (Final Interview)

While this view of engineering design might suggest a fairly complex understanding, other instances included these conceptual categories in addition to at least one other category; in other words, the participant took into consideration other important facets of engineering design.

Combining four conceptual categories. Seven participants across eight instances discussed a substantial number of aspects of engineering design that could be classified into four conceptual categories simultaneously. These participants' descriptions were thought to convey a much more complex understanding of engineering design at these points in time than those who were only classified into one, two, or three categories. I identified three possible combinations of four conceptual categories in the data (Figure 4d).

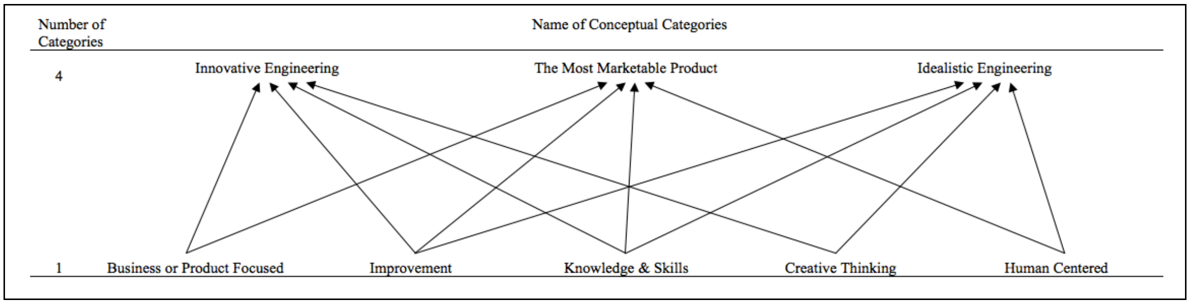


Figure 4d. Combinations of four conceptual categories of engineering design

Innovative engineering. This combination included the following four conceptual categories of engineering design: *Business or Product Focused, Improvement*, *Knowledge and Skills,* and *Creative Thinking.* Individuals who described engineering design in this way not only recognized the business and professional engineering aspects that go into design, but also the need for creative and innovative thinking that engineers will ideally possess, which could lead to better products or solutions. Three participants—Ken, Kristy, and Ralph—across three instances discussed aspects of engineering design across all four of the above conceptual categories. In Ralph's initial concept map (Figure 4e), he included many of the aspects of engineering design that are part of this combination of conceptual categories. Some participants at various instances were classified in more categories (all five) and conveyed a more integrated understanding of engineering design.

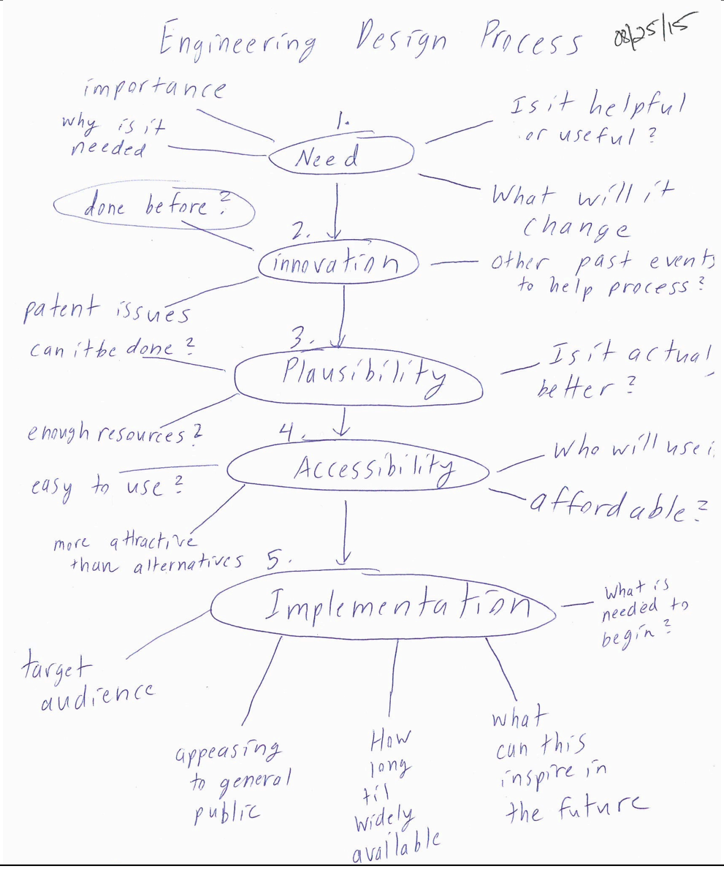


Figure 4e. Ralph's initial concept map

The most marketable product. This combination included the following four conceptual categories: *Improvement, Knowledge and Skills, Business or Product Focused,* and *Human Centered.* This combination described engineering in the business context as requiring the use of knowledge and skills in addition to information about the user to create the best possible product. This description also recognized the need for professional engineers to collaborate and utilize specialized knowledge and skills in design. Three participants across three instances—Haylee, Sasha, and Xandra at the beginning or mid-point in the academic year—discussed enough aspects of engineering design to classify them into all four of these conceptual categories. Xandra's description of engineering represented many of the aspects of engineering design that encompass this combination of conceptual categories of engineering design, and exemplified her complex understanding at this time:

> Engineering is about responding to consumer needs a lot of the times. Also of course.... like laws. In the sense that, I know in California… they can get very specific about like how you need to construct a building because there's earthquakes here and stuff like that. So, it's responding to consumer needs, laws, user wants. But using of course, the physical sciences and the life sciences to respond to them, to really optimize that knowledge for human benefit… Engineering is about sometimes using improving existing technology… improving and going through trials.. constantly improving how something works. (Initial Interview)

Idealistic engineering. This combination included the following four conceptual categories: *Improvement, Knowledge and Skills, Creative Thinking,* and *Human Centered.* With idealistic engineering, one can utilize creative and innovative thinking, knowledge and skills from themselves and others, and create the best possible design to meet all the needs of the user. This view is idealistic because it does not require the engineer to work within constraints, have concrete goals, or create a final product of any kind. This view of engineering design sees it as a never-ending process where engineers can use all of their tools (knowledge, technology, creativity, user insight) to constantly improve a design; there is no concrete end to the process.

Only one individual—Monty—at two separate instances discussed enough aspects of engineering design to classify her descriptions into all four of these conceptual categories. She described all the aspects of engineering design that went on at her school placement, which demonstrated her very complex understanding of engineering design:

> They have like their physics section where they're really understanding what goes into whatever they're making. Like what powers that? What you can do to change it? All those kinds of things. And then they go in the computer lab and they know how to design it, and they're learning the kind of trial and error, like, will this look good? Will this not look good? Is this like practical, sustainable? All that kind of stuff. And then obviously, they're building it, [in the] machine shop, and then making it look really good in the art room. And so, I guess I didn't really understand before how much detail there is, and when you really break it down and you're actually teaching someone the engineering process, how much there is to think about. (Winter Interview)

Integrated understanding of engineering design. If enough aspects of engineering design were discussed at a particular instance to classify a participant's description into all five conceptual categories of engineering design (which also included the sixth—*Basic NGSS*—since all participants across all instances were included in this category), the description was thought to convey an integrated understanding of the many complexities and facets of engineering design.

Table 4f

Combining Multiple Conceptual Categories of Engineering Design

Conceptual Categories	Criteria for Inclusion	Participants	Instances (only in this category)
1. Business or Product Focused 2. Improvement	*The Best Product* The combination of these conceptual categories indicates the understanding of engineering design and the need to create the best products that need business considerations through the process of optimization. This category also recognizes how engineering often builds off the work of others to make better products.	Haylee Anthony	Initial Interview Post-Summer Interview
1. Business or Product Focused 2. Knowledge & Skills	*Making a Product* This combination of conceptual categories indicates the understanding that to create a product in a business-centered engineering setting, one must have the requisite knowledge and skill (or know how to research and learn them).	Adam	Final Interview
1. Improvement 2. Knowledge & Skills	*Learning through Improvement* This combination of conceptual categories indicates an understanding of how engineers can use their knowledge and skill to create designs, and that through making iterative improvements on those designs, they can apply and/or learn further knowledge and skills throughout the process.	David Kayla Saul	Initial Interview Final Interview Post-Summer Interview
1. Improvement 2. Creative Thinking	*Improvement through Innovation* The combination of these conceptual categories indicates an understanding of the need for creative and innovative thinking in order to improve engineering designs. This recognizes that a good design requires elements of creativity that make it better than other designs that may solve the same problem.	Monty	Initial Interview
1. Knowledge & Skills 2. Creative Thinking	*The Engineering Mind* The combination of these conceptual categories indicates an understanding of how an engineer has a particular mind, which seeks out and uses knowledge and skills across multiple areas (science, math, technology, etc.) and uses them creatively to develop innovative designs. This conception focuses on the mind of the engineer and how they think, over what they do.	Rick	Winter Interview

1. Knowledge & Skills 2. Human Centered	*Shared Knowledge* The combination of these two conceptual categories indicates a view of engineering as a knowledge and skills based endeavor, which centers around the needs and/or collaboration of people. This is a fairly basic view that sees engineering as using one's background (science, math, technology, etc.) to solve a problem faced by humans. This view doesn't take into consideration the process by which problems are solved, however.	Kari	Final Interview
1. Improvement 2. Human Centered	*Improving for Humanity* The combination of these two conceptual categories indicates a view of engineering that involves creating the best solution to a problem or need for humans, by humans. This view doesn't take into consideration the process by which this is done, nor whether it results in a product or object that can be used.	Kari	Initial Interview
1. Business or Product Focused 2. Human Centered	*User-Friendly Products* The combination of these two conceptual categories indicates a view of engineering as the development of a product for sale that meets the demands and considerations of the users.	Nick	Winter Interview
1. Creative Thinking 2. Human Centered	*Empathetic Innovation* This combination of conceptual categories demonstrates a view of engineering design that focuses on the human element, both of the engineer themselves, and the potential users of what the engineer designs. This view centers around the internal factors of the people involved in the engineering design process; users and engineers.	Rick	Initial Interview
1. Business or Product Focused 2. Improvement 3. Knowledge & Skills	*Professional Engineering* The combination of these conceptual categories indicates the understanding of engineering design in a professional setting where engineering must utilize their knowledge and skills to create products that are better than the competition's. They do so by making iterative improvements to their own designs or the design of others.	Caitlyn Dana David Josh Kurt Carlos	Initial Interview Focus Group Winter Interview Focus Group Focus Group Post-Summer Interview

1. Business or Product Focused 2. Improvement 3. Creative Thinking	*Elon Musk Mentality* The combination of these conceptual categories indicates an understanding of how the most creative engineers can leverage their knowledge and skill in the business world to develop innovative and novel solutions to engineering problems. This conception views engineers much like Elon Musk, who has developed some of the best, most creative, and most innovative solutions in engineering, even if they are not necessarily in his "wheelhouse".	Rick Zeb	Post-Summer Interview Initial Interview Post-Summer Interview Winter Interview
1. Knowledge & Skills 2. Business or Product Focused 3. Human Centered	*Informed Product Design* This combination of conceptual categories indicates a relatively complex understanding of engineering design in the business context. This view includes the need to use knowledge and skills, in addition to considerations for business and the user to create a product that can be sold.	Haylee Xandra	Final Interview Post-Summer Interview
1. Knowledge & Skills 2. Improvement 3. Human Centered	*The Best Design* This combination of conceptual categories indicates the need to use knowledge and skills in addition to information about the user to develop the best possible design either collaboratively or on one's own.	Macy Ralph Sandra Sasha	Focus Group Winter Interview Focus Group Final Interview
1. Creative Thinking 2. Improvement 3. Human Centered	*The Most Innovative Design* This combination of conceptual categories indicates an idealistic view of engineering design where the engineer is able to constantly strive for the best possible design that is not only creative, but also takes into consideration those who would benefit from the design.	Monty	Final Interview
1. Business or Product Focused 2. Improvement 3. Knowledge & Skills 4. Creative Thinking	*Innovative Engineering* The combination of these four conceptual categories indicates that not only does the individual understand how professional engineering works (discussed above), but also that innovative and creative thinking is an essential skill for an engineer to have if they seek to create the best possible product or solution.	Ken Kristy Ralph	Focus Group Focus Group Initial Interview
1. Knowledge & Skills 2. Business or Product Focused 3. Improvement 4. Human Centered	*The Most Marketable Product* The combination of these four conceptual categories demonstrates an understanding that engineering in the business context requires knowledge, skills, and information about the user to create the best product. This also recognizes the need for engineers to collaborate.	Haylee Sasha Xandra	Winter Interview Initial Interview Winter Interview

1. Improvement 2. Knowledge & Skills 3. Creative Thinking 4. Human Centered	*Idealistic Engineering* The combination of these four conceptual categories indicates that engineering design is viewed in an idealistic manner where one can utilize creative and innovative thinking, knowledge and skills from themselves and other, and create the best possible design to meet all the needs of the user. This view is idealistic because it does not require the engineer to work within constraints, have concrete goals, or create a final product	Monty	Post-Summer Interview Winter Interview
1. Business or Product Focused 2. Improvement 3. Knowledge & Skills 4. Creative Thinking 5. Human Centered	*Integrated Understanding* All conceptual categories for engineering design were significantly addressed by participants, which indicates that they have an integrated understanding of the many facets of engineering design relative to the other instances in the data.	Xandra Zeb	Initial Interview Final Interview Final Interview

Not only did these descriptions demonstrate an understanding of the process of engineering design and the need to improve products or solutions, but they also recognized business considerations, the human element, innovative and creative thinking, and the knowledge and skills required to do engineering. Two individuals—Xandra and Zeb—across three separate instances (Xandra addressed them in her initial interview and again in her final interview) discussed enough aspects of engineering design to classify their descriptions into all five focus categories (and also the *Basic NGSS* category). Because these individuals discussed a wide range of aspects of engineering design within one particular instance, they were thought to have conveyed an integrated understanding of engineering design within the data set.

Level 3 Findings: Considering Experience and Context

While establishing conceptual categories for participants at particular instances provides an indication of their view or understanding at a given point in time, it does not give a full picture of that participant's or of all participants' conceptions of engineering design. To gain a more complex understanding of participants' conceptions of engineering design, the conceptual categories or combination of categories that they were classified within were examined side-by-side with other factors including time in the classroom (only for prospective and preservice teachers), teaching or education experience (indicated by a participant's position along the learning-to-teach continuum), prior experience with engineering, classroom context, and demographic information. Each of these factors is broken down into its constituent parts (if applicable) and is described in more detail below.

Findings by Experience

Conceptual categories of engineering design for participants were compared to their experience in multiple ways. Experience was broken into four major areas: time throughout the academic year (only presented for prospective and preservice teachers), participants' place along the learning-to-teach continuum, prior experience with engineering (including formal and informal engineering contexts and familiarity with engineers), and classroom context.

Table 4g

Conceptual Categories of Engineering Design by Group, Participant, and Instance

			Conceptual Category**					
Group	**Partici-pant**	**Instance**	*Basic NGSS*	*Improve-ment*	*Business or Product Focused*	*Know-ledge & Skills*	*Creative Think-ing*	*Human Centered*
Prospective Teacher	Anthony	Initial	🟦					
		Post	🟦	🟪	🟩			
		Summer	🟦	🟪	🟩			
		Winter	🟦	🟪				
		Final	🟦	🟪				
	Carlos	Initial	🟦			🟨		
		Post	🟦	🟪	🟩	🟨		

		Summer	🟦	🟪	🟩	🟧		
		Winter	🟦		🟩			
		Final	🟦		🟩			
	Monty	Initial	🟦	🟪			🟥	
		Post	🟦	🟪		🟧	🟥	🟨
		Summer	🟦	🟪		🟧	🟥	🟨
		Winter	🟦	🟪		🟧	🟥	🟨
		Final	🟦	🟪			🟥	🟨
	Nick	Initial	🟦			🟧		
		Post	🟦	🟪				
		Summer	🟦	🟪				
		Winter	🟦		🟩			🟨
		Final	🟦	🟪				
	Ralph	Initial	🟦	🟪	🟩	🟧	🟥	
		*Post	🟦					
		Summer	🟦					
		Winter	🟦	🟪		🟧		🟨
		Final	🟦	🟪				
	Rick	Initial	🟦				🟥	🟨
		Post	🟦	🟪	🟩		🟥	
		Summer	🟦	🟪	🟩		🟥	
		Winter	🟦			🟧	🟥	
		Final	🟦			🟧		
	Saul	Initial	🟦		🟩			
		Post	🟦	🟪		🟧		
		Summer	🟦	🟪		🟧		
		Winter	🟦		🟩			
		Final	🟦		🟩			
	Xandra	Initial	🟦	🟪	🟩	🟧	🟥	🟨
		Post	🟦		🟩	🟧		🟨
		Summer	🟦		🟩	🟧		🟨
		Winter	🟦	🟪	🟩	🟧		🟨
		Final	🟦	🟪	🟩	🟧	🟥	🟨
	Zeb	Initial	🟦	🟪	🟩		🟥	
		Post	🟦	🟪	🟩		🟥	
		Summer	🟦	🟪	🟩		🟥	
		Winter	🟦	🟪	🟩		🟥	
		Final	🟦	🟪	🟩	🟧	🟥	🟨
Preservice Teacher	Adam	Initial	🟦	🟪				
		Winter	🟦	🟪				
		Final	🟦		🟩	🟧		
	Caitlyn	Initial	🟦	🟪	🟩	🟧		
		Winter	🟦					
		Final	🟦	🟪				
	David	Initial	🟦	🟪		🟧		
		Winter	🟦	🟪	🟩	🟧		
		Final	🟦	🟪				
	Haylee	Initial	🟦	🟪	🟩			
		Winter	🟦	🟪	🟩	🟧		🟨
		Final	🟦		🟩	🟧		🟨
	Kari	Initial	🟦	🟪				🟨
		Winter	🟦					🟨
		Final	🟦			🟧		🟨

Kayla	Initial	🟦		🟩			
	Winter	🟦	🟪				
	Final	🟦	🟪		🟧		
Molly	Initial	🟦					
	Winter	🟦					
	Final	🟦	🟪				
Sasha	Initial	🟦	🟪	🟩	🟧		🟨
	Winter	🟦					🟨
	Final	🟦	🟪		🟧		🟨

*Ralph did not have a post-summer interview, therefore the data from this instance only consists of his concept map. This limited data for this instance might have affected the conceptual category that he was placed into.
**Blue = Basic NGSS; Purple = Improvement; Green = Business or Product Focused; Orange = Knowledge & Skills; Red = Creating Thinking; and Yellow = Human Centered

Findings over time: Prospective and preservice teachers. Prospective teachers were interviewed and created concept maps at four separate points throughout the study year: once before their summer 5-week intensive internship experience, once after this summer internship experience, once midway through the academic year (in winter), and last, at the end of the academic and study year in late spring. Preservice teachers were interviewed at three separate points throughout the study year: once before the school year (in August), once midway through the year (in winter), and last, at the end of the study year in late spring. They only created concept maps in their initial and final interviews, and analyzed two example concept maps during their winter interview.

Prospective teachers. Each instance (interview and associated concept map) for all prospective teacher participants are shown in Table 4g above, along with the conceptual categories of engineering design that each was classified into. All participants in this group discussed the *Basic NGSS* category in all instances, but only two participants at two instances fell exclusively within this category without also being included in another conceptual category. One of these instances was Ralph's post-summer interview, which it is important to note, was gathered only from his concept map; his interview audio was lost, and thus, no transcript could be analyzed. Because instances were uniformly classified into this category, *Basic NGSS* was not included in the total count that participants were classified into at a given instance. Given this distinction, participants in the prospective teacher group were classified into one to five of the five major conceptual categories at a given instance.

Increase in complexity of understanding. Some prospective teachers appeared to gain a more complex understanding of engineering design over time throughout the study year as indicated by an increase in the number of conceptual categories they were classified into at later instances in the data. For example, while Anthony started the study only identifying aspects of engineering design that fell into the *Basic NGSS* conceptual category, his descriptions became more complex over time. By the end of the study year, he provided a slightly more complex description of engineering design, identifying enough aspects of engineering design to classify his description into the *Improvement* conceptual category as well. While this was a slight increase, Anthony's peak in complexity of understanding actually occurred during his post-summer interview, where he was classified into three conceptual categories: *Basic NGSS, Improvement,* and *Business or Product Focused*.

Other participants with an increase in the complexity of their descriptions of engineering design included Monty and Zeb. Monty began the study year identifying enough aspects of engineering design to be classified in two major conceptual categories—*Improvement* and *Creativity*—in addition to the *Basic NGSS* category and ended the year being classified into one additional category, *Human Centered.* Much like

Anthony, however, her final interview did not demonstrate the *most* complex level of her understanding. In Monty's post-summer and winter interviews, she was classified into five conceptual categories— *Basic NGSS, Improvement, Creative Thinking, Human Centered,* and *Knowledge and Skills*—that demonstrated her personal peak in describing engineering design.

Zeb was unlike these other two participants (Anthony and Monty) in that his most complex description of engineering design did not occur in the middle of the study year, but actually increased over time. In his initial, post-summer, and winter interviews, Zeb discussed enough aspects of engineering design to classify him into four conceptual categories: *Basic NGSS, Improvement, Business or Product Focused,* and *Creative Thinking*. His understanding appeared to stay unchanged throughout the study year until the final interview, in which he discussed enough aspects of engineering design to classify him into all six of the conceptual categories, indicating that by the end of the study year, he was able to convey an integrated understanding of engineering design.

Decrease in complexity of understanding. Some prospective teachers had a decrease in the complexity of their engineering design description as indicated by a decrease in the number of conceptual categories that they were classified into at a given instance over time. Ralph had the most noticeable decrease over time in the number of conceptual categories. He began the study year discussing enough aspects of engineering design to classify him into five conceptual categories: *Basic NGSS, Improvement, Business or Product Focused, Knowledge and Skills,* and *Creative Thinking.* In his winter interview, this number of categories decreased to four (*Basic NGSS, Improvement,* *Knowledge and Skill,* and *Human Centered),* and by his final interview, he was only classified into two categories— *Basic NGSS* and *Improvement.* Rick was the only other prospective teacher whose complexity of descriptions of engineering design decreased, but only slightly. In his initial interview, he discussed enough aspects of engineering design to be classified into three conceptual categories: *Basic NGSS, Creative Thinking,* and *Human Centered*. By his final interview, Rick was only classified into two categories— *Basic NGSS* and *Knowledge and Skills.*

Peak or "U" in understanding over time. Some prospective teachers had either their lowest or highest complexity of description midway through the study year (in either their post-summer or winter interviews). For example, while Anthony had a slight increase in the complexity of his descriptions of engineering design over time (discussed above), his peak actually occurred in his post-summer interview, where he identified enough aspects of engineering design to be classified into three conceptual categories—*Basic NGSS, Improvement,* and *Business or Product Focused*—rather than just one. Similarly, Monty also had her highest peak midway through the study year, being classified into five major conceptual categories— *Basic NGSS, Improvement, Knowledge and Skill, Creative Thinking,* and *Human Centered*—in both her post-summer and winter interviews.

Some prospective teachers who had a decrease or had no change in the complexity of their understanding of engineering design between their initial and final interviews also had their peak midway through the study year. Rick's description was classified into four conceptual categories— *Basic NGSS, Improvement, Business or*

Product Focused, and *Creative Thinking*—in his post-summer interview before then decreasing to three categories— *Basic NGSS, Knowledge and Skills,* and *Creative Thinking*—in winter, and finally, to his lowest in the final interview. Carlos had no change between his initial and final interviews, however, his peak was during his post-summer interview where he discussed enough aspects of engineering design to classify him into four conceptual categories— *Basic NGSS, Improvement, Business or Product Focused,* and *Knowledge and Skills.* Nick and Saul, similarly, had no change between their initial and final interviews; each discussed enough aspects of engineering design to classify them into two conceptual categories (including *Basic NGSS*). However, each of them had peaks in the complexity of their understanding midway through the year. Nick was classified into three conceptual categories— *Basic NGSS, Business or Product Focused,* and *Human Centered*—in his winter interview, and Saul was classified into the *Basic NGSS, Improvement,* and *Knowledge and Skills* conceptual categories.

Lastly, Xandra was a special case where the complexity of her description of engineering design throughout the study year took the shape of a “U”. She was one of the few individuals to present an integrated description of engineering design in both her initial *and* final interviews. This means that she discussed enough aspects of engineering design in those interview and in the associated concept maps to be classified into all of the conceptual categories for engineering design: *Basic NGSS, Improvement, Business or Product Focused, Knowledge and Skills, Creative Thinking,* and *Human Centered.* This integrated understanding, however, was not present in her other two midyear interviews. In Xandra’s post-summer interview, she was only classified into four conceptual categories— *Basic NGSS, Business of Product Focused, Knowledge and Skills,* and *Human Centered*—which was her lowest complexity of understanding for the study year. While the complexity of her description of engineering design did increase slightly in her winter interview to five conceptual categories— *Basic NGSS, Improvement, Business or Product Focused, Knowledge and Skills,* and *Human Centered*—this was still not as complex as the integrated understanding she demonstrated in her initial and final interviews.

Preservice teachers. Each instance (interview and associated concept map) for all preservice teacher participants are shown in Table 4g above, along with the conceptual categories of engineering design that each was classified into. All participants in this group were in the *Basic NGSS* category in all instances, but only two participants at three instances fell exclusively within this category without also being included in another conceptual category. Caitlyn only discussed enough aspects of engineering design in her winter interview to be classified into the *Basic NGSS* conceptual category, as did Molly in both her initial and winter interviews.

Increase in complexity of understanding. Some preservice teachers appeared to provide a more complex understanding of engineering design over time throughout the study year as indicated by an increase in the number of conceptual categories they were classified into at later instances in the data. Several participants had modest increases in the number of conceptual categories that they were classified into from the initial interview to the final interview. Molly was only categorized in the *Basic NGSS* category at the beginning of the study, but in her final interview, also discussed enough aspects of engineering design to be classified in the *Improvement* conceptual category as well. Adam, Kayla, and Haylee also had slight increases in the complexity of their descriptions of engineering design over time. Adam started the study year with his description classified into only two conceptual categories— *Basic NGSS* and *Improvement*—but increased this to three categories— *Basic NGSS, Business or Product Focused,* and *Knowledge and Skills*—by his final interview. Similarly, Kayla was only classified into two categories in her initial interview— *Basic NGSS* and *Business or Product Focused*— but increased this to three categories— *Basic NGSS, Improvement,* and *Knowledge and Skills*—by her final interview. Last, Haylee identified enough aspects of engineering design in her initial interview to be classified into three conceptual categories— *Basic NGSS, Improvement,* and *Business or Product Focused*—and increased the complexity of her description to include four conceptual categories— *Basic NGSS, Business or Product Focused, Knowledge and Skills,* and *Human Centered*—by her final interview.

Decrease in complexity of understanding. Some preservice teachers had a decrease in the complexity of their description of engineering design as indicated by a decrease in the number of conceptual categories that they were classified into at a given instance over time. David began the study year by identifying enough aspects of engineering design to be classified into three conceptual categories— *Basic NGSS, Improvement,* and *Knowledge and Skills*. By his final interview, there was a slight decrease in the complexity of his description because, in this interview, he was only classified in the *Basic NGSS* and *Improvement* categories. Sasha also showed a modest decrease in the complexity of her description of engineering design. Her description was classified into five conceptual categories— *Basic NGSS, Improvement, Business or Product Focused, Knowledge and Skills,* and *Human Centered*—in her initial interview, but only four—*Basic NGSS, Improvement, Knowledge and Skills,* and *Human Centered*—in her final interview. The largest decrease was seen in Caitlyn, whose description was classified into four conceptual categories at the beginning of the study— *Basic NGSS, Improvement, Business or Product Focused,* and *Knowledge and Skills*—but only two categories at the end— *Basic NGSS* and *Improvement.*

Peak or "U" in understanding over time. Some preservice teachers either conveyed their lowest or highest complexity of understanding midway through the study year (in their winter interviews). David and Haylee both provided a more complex description of engineering education in their winter interview than they did in either their initial or final interviews. David reached his peak in complexity of description when he discussed enough aspects of engineering design in his midyear interview to be classified into four conceptual categories— *Basic NGSS, Improvement, Business or Product Focused,* and *Knowledge and Skills*—compared to the three categories in his initial interview, and the two categories in his final interview. Haylee was classified into five conceptual categories— *Basic NGSS, Improvement, Business or Product Focused, Knowledge and Skills,* and *Human Centered*—in her winter interview, while only being classified in three in her initial interview, and four in her final interview.

Some participants conveyed a complexity of understanding of engineering design throughout the study year that took the shape of a "U", where their winter interview classified them in the fewest conceptual categories compared to their initial and final interviews. For example, while Caitlyn and Sasha's descriptions decreased in their complexity of understanding between their initial and final interviews, their winter interview actually had the lowest number of conceptual categories that they were classified into. In Caitlyn's winter interview, she provided the least complex description of engineering design, classified only in the *Basic NGSS* category, compared to four in her initial interview, and two in her final interview. Similarly, Sasha had a dip in the complexity of her description in her winter interview, only being classified into two categories— *Basic NGSS* and *Human Centered*—compared to five in her initial interview, and four in her final interview. Last, Kari had a slight dip in the complexity of description in winter, only being classified in two conceptual categories— *Basic NGSS* and *Human Centered*—compared to three categories in her initial interview— *Basic NGSS, Improvement,* and *Human Centered*—and her final interview— *Basic NGSS, Knowledge and Skills,* and *Human Centered.*

Findings along the learning-to-teach continuum. Because the prospective and preservice teacher participants were interviewed and/or created concept maps at multiple times throughout the study year, there were multiple possible instances of their description that could be used in additional analyses. I decided that the final interview and concept map data of the prospective and preservice teachers would be compared to the focus group data from the practicing teachers and teacher educators (Table 4h). This was done to make a comparison among these groups after they had some background and experience in the classroom, but at varying intensities—the preservice teacher education program was much more intense than the internship over the course of the study year. Therefore, the full range of experience (from little experience in the classroom to many years of experience) could be examined. This was also the case for the comparisons of context, experience, and demographics done across all participants (discussed below).

It is important to remember that while the prospective and preservice teachers were interviewed multiple time throughout the study year and had multiple opportunities to reflect on engineering design in the process, the practicing teachers and teacher educators only participated in a single focus group interview. This may have limited their discussion on engineering design as they did not have as many opportunities to reflect and come back to it like the other teacher groups did. Despite this, the findings from comparing these group are discussed below.

Comparing complexity of understanding of engineering design. The prospective teacher participants were classified into an average of three conceptual categories for engineering design in their final interviews—the focal instance in the study year for these comparisons—and with a range of one to six categories. Preservice teachers were also classified into an average of three conceptual categories in their final interviews with a range of one to four categories. Practicing teachers had an average of four conceptual categories with a range of four to five categories, and finally, teacher educators were classified into an average of two categories, with a range of one to two categories (see Table 4h).

Table 4h

Conceptual Categories of Engineering Design Along the Learning-to-Teach Continuum

			Conceptual Category*					
Group	**Instance**	**Participant**	*Basic NGSS*	*Improvement*	*Business or Product Focused*	*Knowledge & Skills*	*Creative Thinking*	*Human Centered*
Prospective Teacher	Final Interview	Anthony	🟦	🟪				
		Nick	🟦	🟪				
		Ralph	🟦	🟪				
		Carlos	🟦		🟩			
		Saul	🟦		🟩			
		Rick	🟦			🟧		
		Monty	🟦	🟪			🟥	🟨
		Xandra	🟦	🟪	🟩	🟧	🟥	🟨
		Zeb	🟦	🟪	🟩	🟧	🟥	🟨
Preservice Teacher	Final Interview	Caitlyn	🟦	🟪				
		David	🟦	🟪				
		Molly	🟦	🟪				
		Kayla	🟦	🟪		🟧		
		Adam	🟦		🟩	🟧		
		Kari	🟦			🟧		🟨
		Sasha	🟦	🟪		🟧		🟨
		Haylee	🟦		🟩	🟧		🟨
Practicing Teacher	Focus Group	Dana	🟦	🟪	🟩	🟧		
		Josh	🟦	🟪	🟩	🟧		
		Kurt	🟦	🟪	🟩	🟧		
		Macy	🟦	🟪		🟧		🟨
		Sandra	🟦	🟪		🟧		🟨
		Ken	🟦	🟪	🟩	🟧	🟥	
		Kristy	🟦	🟪	🟩	🟧	🟥	
Teacher Educator	Focus Group	Patty	🟦					
		Jasmine	🟦			🟧		
		Sally	🟦			🟧		

*Blue = Basic NGSS; Purple = Improvement; Green = Business or Product Focused; Orange = Knowledge & Skills; Red = Creating Thinking; and Yellow = Human Centered

While the prospective teacher group was the only group that included participants who conveyed an integrated description of engineering design, the practicing teacher group conveyed the most complex understanding on average overall. These findings indicate that while some prospective teachers might have provided an integrated description of engineering design, those who had more experience in the classroom, especially those who had some focus on engineering, tended to express a more complex understanding of engineering design overall than any other group along the learning-to-teach continuum.

The group with the lowest complexity of understanding was the teacher educator group. This might be because these individuals were not teaching engineering in the classroom setting, but rather only teaching about basic engineering standards present in the *Next Generation Science Standards* (NGSS Lead States, 2013). The preservice teacher group also had a fairly low complexity of description of engineering design. This might also be because of their lack of experience in practicing engineering in the classroom and the focus on basic engineering standards from the *NGSS*.

Comparing conceptual categories along the learning-to-teach continuum. Some groups along the learning-to-teach continuum were classified into certain conceptual categories of engineering design more or less often than others (Table 4i). Some groups viewed engineering design as more creative, business-oriented, human centered, based on knowledge and skills, or a process of constant improvement than others.

The practicing teacher group, having the most complex understanding of engineering design, also had the highest overall average (66%) of being classified into conceptual categories of engineering design. They were also the only group that had all participants be classified into both the *Improvement* and *Knowledge and Skills* categories, and had at least two participants be classified in all five major conceptual categories. This indicates that not only did these practicing teachers have a complex understanding of engineering design, they also represented a wide range of views of engineering design that spanned all conceptual categories established across the data. Although all categories were represented by this group, a majority of participants held a view of engineering design as it being based on knowledge and skill and as a process of constant improvement.

The prospective teachers had the next highest overall average (42%) of being classified into conceptual categories of engineering design. They also had at least three participants classified in all five major conceptual categories indicating that they, too, represented a wide range of views of engineering design that spanned all conceptual categories of engineering design. Along with the practicing teacher group, the prospective teachers were the only other ones that discussed enough aspects of engineering design to classify participants into the *Creative Thinking* category and had the highest percent (33%) of participants classified into this category. While the prospective teacher group had the largest percentage (67%) of participants classified into the *Improvement* category, there was also a relatively even distribution of participants classified into the remaining four major conceptual categories—44% in the *Business or Product Focused* category, and 33% in the *Knowledge and Skills, Creative Thinking,* and *Human Centered* categories. This indicates that these prospective teachers had a wide variety, but fairly even distribution of views of engineering design across the conceptual categories established across the data.

The preservice teachers had a slightly lower overall average (38%) of being classified into conceptual categories of engineering design than the prospective teachers.

This group also had a relatively high distribution of participants being classified into conceptual categories, with at least two participants being classified in four of the five major categories—not including the *Creative Thinking* category. The lowest percent (25%) of participants were classified into the *Business or Product Focused* category, and the highest percent (63%) were classified into both the *Improvement* and *Knowledge and Skills* categories. This indicates that, overall, these preservice teachers viewed engineering design as being based on knowledge and skill and as a process of constant improvement -- similar to the overall views of the practicing teachers. They were also less likely than the prospective and practicing teachers to view engineering design as business or product-driven.

The teacher educator group had the least complex view of engineering design and had the lowest number of conceptual categories represented by participants, with an overall average of being classified into conceptual categories of engineering design of only thirteen percent. Only two of the three participants discussed enough aspects of engineering design to be classified into any of the major categories of engineering design and they were both classified into the *Knowledge and Skills* category. This indicates that these teacher educators were more likely to view engineering design as being based on knowledge and skills, however their primary view of engineering design was based on the basic description provided in the *Next Generation Science Standards* (NGSS Lead States, 2013). This group had the least complex and least diverse view of engineering design of all the groups along the learning-to-teach continuum, and rather, stuck closely to the *NGSS* view of engineering design.

Table 4i

Frequency of Conceptual Categories of Engineering Design Along the Learning-to-Teach Continuum

	Major Conceptual Category					
Group	*Improvement*	*Business or Product Focused*	*Know-ledge & Skills*	*Creative Thinking*	*Human Centered*	**Overall Average**
Prospective Teacher	67%	44%	33%	33%	33%	**42%**
Preservice Teacher	63%	25%	63%	0%	38%	**38%**
Practicing Teacher	100%	71%	100%	29%	29%	**66%**
Teacher Educator	0%	0%	67%	0%	0%	**13%**

Findings by prior experience with engineering. In the prospective and preservice teachers' initial interviews they were asked about their prior experience with engineering, including any courses they had taken, informal engineering experiences, or familiarity with professional engineers. Practicing teachers and teacher educators were also asked about this individually at the beginning of their focus group interviews. These responses were classified into two major groups: experience with formal and informal engineering. These groups were further divided into smaller groupings, including engineering courses, research, and professional engineering for formal engineering, and non-engineering courses that incorporate engineering, engineering outreach, and doing informal engineering. While non-engineering courses are still considered *formal* coursework, I include it in the informal engineering category because the course is not explicitly teaching formal *engineering* content. Familiarity with engineers was also documented regardless of the type of relationship (e.g., close family, friends, coworkers, etc.). Each of these types of formal and informal engineering experiences as well as familiarity with engineers were compared across participants with the conceptual categories that they were classified into and described below (see Table 4j).

Table 4j

Participants' Conceptual Category Classification by Experience with Formal and Informal Engineering

Teacher Group	**Name**	**Conceptual Category (*Color Coded)**	**Formal Engineering**			**Informal Engineering**			**Familiarity with Engineer(s)**
			Eng. Course	Eng. Research	Professional Eng. Job	Non-Eng. Courses	Eng. Outreach	Doing Informal Engineering	
Prospective	Zeb	🟦🟪🟩🟧🟥🟨		X		X			X
	Xandra	🟦🟪🟩🟧🟥🟨	X				X	X	X
	Saul	🟦🟩							X
	Rick	🟦🟧						X	X
	Ralph	🟦🟪	X			X			X
	Nick	🟦🟪	X						X
	Monty	🟦🟪🟥🟨				X			X
	Carlos	🟦🟩				X		X	X
	Anthony	🟦🟪						X	X
Preservice	Molly**	🟦🟪							
	Kari	🟦🟧🟨							
	Adam	🟦🟩🟧	X			X			
	Caitlyn	🟦🟪	X			X			
	Sasha	🟦🟪🟧🟨	X						X
	Kayla	🟦🟪🟧🟨	X			X			
	Haylee	🟦🟩🟧🟨				X			
	David	🟦🟪				X			
Practicing	Ken	🟦🟪🟩🟧🟥				X			X
	Kurt	🟦🟪🟩🟧	X	X			X		X
	Dana	🟦🟪🟩🟧				X		X	X
	Josh	🟦🟪🟩🟧			X				X
	Kristy	🟦🟪🟩🟧🟥				X		X	X
	Macy	🟦🟪🟧🟨	X			X		X	
	Sandra	🟦🟪🟧🟨		X	X				
Educators	Sally	🟦🟧				X			X
	Patty	🟦	X			X		X	
	Jasmine	🟦🟧					X		X
Total for each type of engineering experience			10	3	2	15	3	8	17

*Blue = Basic NGSS; Purple = Improvement; Green = Business or Product Focused; Orange = Knowledge & Skills; Red = Creating Thinking; and Yellow = Human Centered

**Background information on engineering experiences was not asked about during initial interview

Formal engineering. Overall, the relationship between prior formal engineering experience and the number of conceptual categories for engineering design that participants were classified into—the indicator for complexity of understanding at a given time—did not appear to have any relationship. There was a large spread when comparing these two variables, with participants having a wide range of complexity of understanding at every level of prior experience with formal engineering (see Table 4k below). For example, Ken had no prior experience with formal engineering, but conveyed one of the most complex descriptions of engineering design. Conversely, Nick and Ralph had some prior experience with formal engineering (engineering courses), but were only classified into two conceptual categories, indicating a fairly low complexity.

This large variation in the data overall might be in part because there were only three smaller groupings within the larger, formal engineering group of prior experience. Because of this, there was a maximum of three areas that participants could indicate, with only two being the most that any participant actually indicated in her or his interviews. Because there appeared to be no larger relationship, each smaller grouping of formal engineering was also explored below to determine if there were any patterns within these smaller divisions of engineering experience across participants.

Engineering courses. Nine participants had prior experience with engineering in the form of taking engineering courses. These participants included the prospective teachers Xandra and Ralph; the preservice teachers Adam, Caitlyn, Sasha, and Kayla; the practicing teachers Kurt and Macy; and the teacher educator Patty. While the complexity of their descriptions of engineering design—indicated by the number of conceptual categories that they were classified into—varied widely across the participants (ranging from two to six), there were some common categories. Eight of the nine participants were classified into the major categories *Improvement* and *Knowledge and Skills*. Also, almost half of all the participants who were classified into the *Human Centered* conceptual category were those who had previous experience with engineering in the form of formal engineering courses.

Engineering research. Three participants had prior experience with engineering in the form of engineering research experience. These participants included the prospective teacher Zeb, and the practicing teachers Kurt and Sandra. These participants tended to provide more complex descriptions of engineering design, being classified into four (Kurt and Sandra) or six (Zeb) conceptual categories. Similar to those who took engineering courses, these participants also tended to be classified into the *Improvement* and *Knowledge and Skills* categories. Additionally, two out of these three participants were classified into the *Human Centered* and *Business or Product Focused* conceptual categories.

Professional engineering. Two participants had prior experience with engineering by being professional engineers prior to working in the classroom context. These participants were practicing teachers Josh and Sandra. These two participants conveyed the same complexity in their descriptions of engineering design, being classified into four conceptual categories each. Both were classified into the *Improvement* and *Knowledge and Skills* categories, like the participants discussed above. However, Josh was classified into the *Business or Product Focused* conceptual category, indicating that his view of engineering design was more business or product centered, whereas Sandra was classified into the *Human Centered* conceptual category, indicating that her view of engineering design was centered more around humans (the users and/or the collaboration of people).

Table 4k

Number of Conceptual Categories and Number of Formal Engineering Groupings by Participant

Participant	Number of Formal Engineering Groupings	Number of Conceptual Categories
Saul	0	2
Rick	0	2
Carlos	0	2
Anthony	0	2
Molly*	0	2
David	0	2
Sally	0	2
Jasmine	0	2
Kari	0	3
Haylee	0	4
Monty	0	4
Monty	0	4
Dana	0	4
Ken	0	5
Kristy	0	5
Patty	1	1
Ralph	1	2
Nick	1	2
Caitlyn	1	2
Adam	1	3
Sasha	1	4
Kayla	1	4
Josh	1	4
Macy	1	4
Zeb	1	6
Xandra	1	6
Sandra	2	4
Kurt	2	4

*Molly was not asked about prior experience with engineering in her initial interview

Informal engineering. Overall, the relationship between prior informal engineering experience and the complexity of description for engineering design hints at a slight increase in participants' complexity of descriptions of engineering design as their informal engineering experience increased. However, as above, there was a large spread in this overall trend when participants had a wide range of complexity of understanding at every level of prior experience with informal engineering. This might be in part because there were only three smaller groupings within the larger, informal engineering group of prior experience. Because of this, there was a maximum of three areas that participants could indicate, with only two being the most that any participant actually indicated in her or his interviews (see Table 4l below).

Interestingly, of participants who had the most informal engineering experience (2 categories indicated), there was a split between participants who had relatively simple descriptions of design (indicated by only being classified into one or two conceptual categories) and those who had relatively complex descriptions (indicated by being classified into four, five, or even six conceptual categories) of engineering design. Each smaller grouping of informal engineering is also explored below to determine if there were any patterns within these smaller divisions of engineering experience across participants.

Courses that incorporate engineering. Fifteen participants had prior experience with engineering in the form of taking non-engineering courses that incorporated aspects of engineering (self-identified by participants). The courses that participants indicated for this grouping of engineering experience typically included science courses with lab components where they had to problem-solve or figure things out on their own without being guided by a teacher or another instructor. These are considered informal engineering experiences, because they are non-engineering courses that informally incorporated aspects of engineering into them, as opposed to teaching formal engineering concepts or practices.

These participants included prospective teachers Zeb, Ralph, Monty, and Carlos; preservice teachers Adam, Caitlyn, Kayla, Haylee, and David; practicing teachers Ken, Dana, Kristy, and Macy; and teacher educators Sally and Patty. The complexity of understanding among participants with this type of prior experience with engineering varied widely. Teacher educator, Patty, was only classified into one category (*Basic NGSS*), whereas prospective teacher, Zeb, demonstrated an integrated understanding of engineering design by being classified into all six conceptual categories. There also was not an apparent pattern among the conceptual categories that these participants were more or less commonly classified into, with all categories represented in a similar frequency as with the total participants overall. This might indicate that this grouping of prior engineering experience might not have had an effect on participants' views of understanding of engineering design.

Engineering outreach. Only three participants had prior experience with engineering in the form of engineering outreach, including going into informal contexts like museums and camps, etc. to teach engineering. These participants were Xandra, a prospective teacher; Kurt, a practicing teacher, and Jasmine; a teacher educator. While these participants' complexity of descriptions of engineering design varied widely, with Jasmine being classified into only two categories, Kurt into four categories, and Xandra into all six, they did have one conceptual category in common. All participants who had prior experience with engineering in the form of engineering outreach were classified into the *Knowledge and Skills* category. This might be an indication that participants who had done engineering outreach before might have had a view of engineering design as being based on knowledge and skills that the engineer should possess and use throughout the process.

Table 4l

Number of Conceptual Categories and Number of Informal Engineering Groupings by Participant

Participant	Number of Informal Engineering Groupings	Number of Conceptual Categories
Saul	0	2
Nick	0	2
Molly*	0	2
Kari	0	3
Sasha	0	4
Josh	0	4
Sandra	0	4
Rick	1	2
Ralph	1	2
Anthony	1	2
Caitlyn	1	2
David	1	2
Sally	1	2
Jasmine	1	2
Adam	1	3
Monty	1	4
Kayla	1	4
Haylee	1	4
Kurt	1	4
Ken	1	5
Zeb	1	6
Patty	2	1
Carlos	2	2
Dana	2	4
Macy	2	4
Kristy	2	5
Xandra	2	6

*Molly was not asked about prior experience with engineering in her initial interview

Doing informal engineering. Eight participants had prior experience with engineering in the form of doing informal engineering, including building or making things, or engaging in engineering problem solving. These participants included prospective teachers Xandra, Rick, Carlos, and Anthony; practicing teachers Dana, Kristy, and Macy; and teacher educator Patty. The complexity of understanding of engineering design of these participants, again, varied widely from one conceptual category to six. There were also no clear patterns in the conceptual categories of engineering design that this group of participants were classified into, with all categories being represented by participants. This might indicate that doing informal engineering did not have had an effect on participants' view or understanding of engineering design.

Familiarity with engineers. Many participants had prior experience with engineering in the form of their familiarity with a professional engineer. Seventeen participants knew at least one professional engineer that they mentioned during an interview. These participants included all nine prospective teachers; preservice teacher Sasha; practicing teachers Ken, Kurt, Dana, Josh, and Kristy; and teacher educators Sally and Jasmine. Because there were so many participants who indicated knowing an engineer, and the number and type of conceptual categories that they were classified into varied widely, there did not appear to be any clear relationship between familiarity with engineers and the view or complexity of understanding of engineering design.

Overall prior experience. When looking at all possible prior experience—including formal and informal—with engineering, some faint trends emerged across all participants. While the overall trend was a rough increase in the complexity of understanding as participants' prior experiences with engineering increased, it also appeared to have a fairly wide spread (see Figure 4f below). There appeared to be a slow increase overall between these two aspects, but there was a very large spread in complexity of understanding when participants had three kinds of prior experience with engineering. Also, a majority of the participants were grouped in the middle of the spread (noted by larger dots in the figure), having moderate prior experience with engineering and also moderate complexity of understanding of engineering design. Overall, it appeared that prior experience with engineering design might be loosely associated with the complexity of understanding of participants.

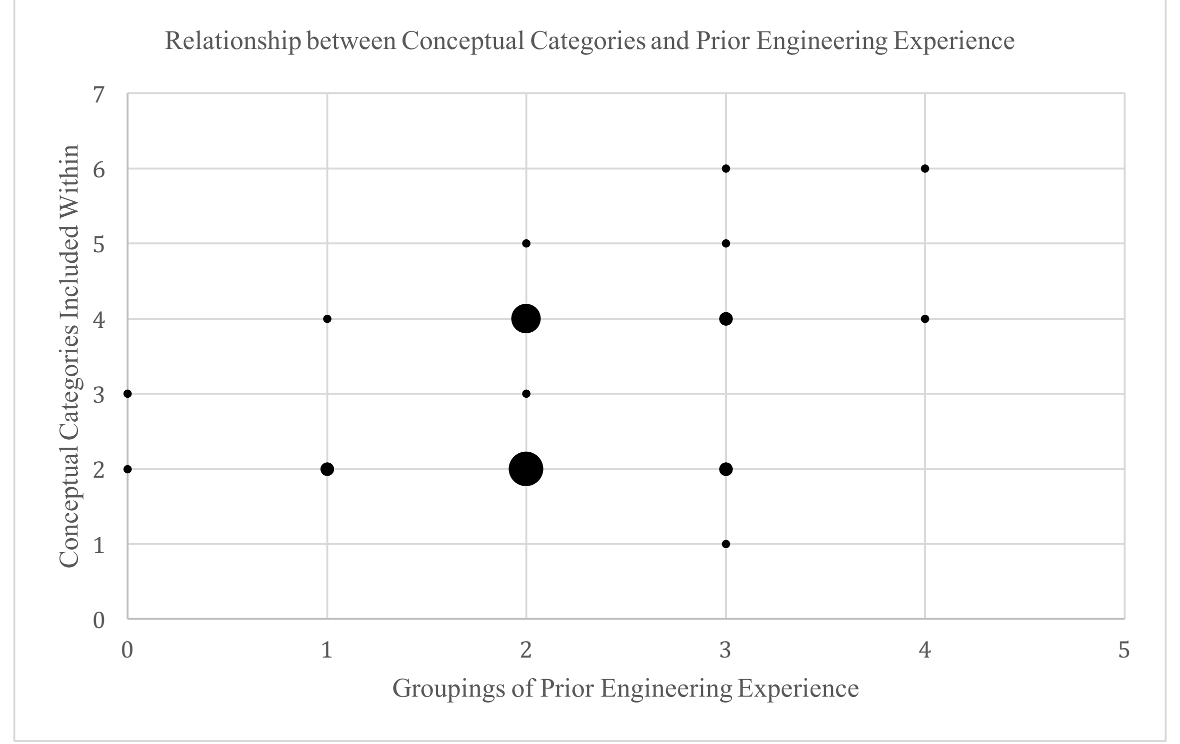


Figure 4f. Relationship between conceptual categories and prior engineering experience

Some prior experience with engineering might be a better indication of participants' likelihood to have certain views or understandings of engineering design.

Participants who had formal engineering experience in the form of engineering courses, research, or being a professional engineer tended to have views of engineering design more in line with the *Human Centered* and *Business or Product Focused* conceptual categories. Also, those who had experience doing professional engineering or engineering research had a more complex understanding of engineering design.

Table 4m

Participants' Conceptual Category Classification by Placement Context

Group	**Participant**	**Conceptual Category****						**Academic Quarter**			
								Summer	*Fall*	*Winter*	*Spring*
Prospective	Zeb	🟦	🟪	🟩	🟧	🟥	🟨	Engineering*	Engineering	Engineering	--
Prospective	Xandra	🟦	🟪	🟩	🟧	🟥	🟨	Engineering	--	--	Engineering
Prospective	Saul	🟦		🟩				Engineering	Engineering	Engineering	Engineering
Prospective	Rick	🟦			🟧			Science	--	--	Science
Prospective	Ralph	🟦	🟪					Engineering	Engineering	Engineering	Engineering
Prospective	Nick	🟦	🟪					Engineering	Engineering	Engineering	--
Prospective	Monty	🟦	🟪			🟥	🟨	Engineering	Engineering	Engineering	--
Prospective	Carlos	🟦		🟩				Engineering	Engineering	--	--
Prospective	Anthony	🟦	🟪					Engineering	Engineering	--	--
Preservice	Molly	🟦	🟪					--	--	Science	Science
Preservice	Kari	🟦			🟧		🟨	--	--	Science	Science
Preservice	Adam	🟦		🟩	🟧			--	--	Science	Science
Preservice	Caitlyn	🟦	🟪					--	Engineering	Engineering	Engineering
Preservice	Sasha	🟦	🟪		🟧		🟨	--	--	Science	Science
Preservice	Kayla	🟦	🟪		🟧		🟨	--	--	Science	Engineering
Preservice	Haylee	🟦		🟩	🟧		🟨	--	Engineering	Engineering	Engineering
Preservice	David	🟦	🟪					--	--	Science	Science
Practicing	Ken	🟦	🟪	🟩	🟧	🟥		Engineering	Engineering	Engineering	Engineering
Practicing	Kurt	🟦	🟪	🟩	🟧			Engineering	Engineering	Engineering	Engineering
Practicing	Dana	🟦	🟪	🟩	🟧			Engineering	Engineering	Engineering	Engineering
Practicing	Josh	🟦	🟪	🟩	🟧			Engineering	Engineering	Engineering	Engineering
Practicing	Kristy	🟦	🟪	🟩	🟧	🟥		Engineering	Engineering	Engineering	Engineering
Practicing	Macy	🟦	🟪		🟧		🟨	Engineering	Engineering	Engineering	Engineering
Practicing	Sandra	🟦	🟪		🟧		🟨	Science	Science	Science	Science

-- indicates that participants were not in a classroom placement or student teaching during the quarter.

*All placement that indicate "engineering" also included science components.

**Blue = Basic NGSS; Purple = Improvement; Green = Business or Product Focused; Orange = Knowledge & Skills; Red = Creating Thinking; and Yellow = Human Centered

Findings by classroom placement. The relationship between participants' classroom placement or teaching context and their view and understanding of engineering design were examined along two dimensions (Table 4m). I discuss whether participants' placements incorporated engineering alongside science to determine if patterns between this and their views and understandings of engineering design emerged.

Engineering vs. science placements. While all prospective, preservice, and practicing teacher participants were in classrooms where science was at least part of the curriculum, only some participants were in classrooms that also incorporated engineering. Because teacher educators were not in classrooms either teaching or observing, they were not included in these findings. Classrooms that were part of the Project-Based Engineering Academy (PBEA) included an engineering component, as was the class at the Eco Academy (EA) taught by Macy. All prospective teachers, with the exception of Rick, were placed in classrooms that incorporated engineering alongside science (at both PBEA and EA). Only the preservice teachers Caitlyn, Haylee, and Kayla were placed in classrooms for at least one quarter that incorporated engineering alongside science (at PBEA). All practicing teachers, with the exception of Sandra at EA, taught in a context where engineering was incorporated alongside science (at PBEA and EA).

Science only classrooms. Participants who were placed in or taught in classrooms that were only focused on science and did not explicitly incorporate engineering included the following: prospective teacher Rick; preservice teachers Molly, Kari, Adam, Sasha, and David; and practicing teacher Sandra. The complexity of understanding of engineering design ranged from being classified into two conceptual categories—in the case of Rick, Molly, and David—into three categories—in the case of Kari and Adam—into four categories—in the case of Sasha and Sandra. Because there was a small range in their complexity of understandings, one can argue that participants who were in these science-only classes tended to have a moderate complexity of understanding of engineering design, with no participant too low or too high. It is also important to note that there were no participants in these types of classrooms who discussed aspects of engineering design that would classify them into the *Creative Thinking* category and only one was classified into the *Business or Product Focused* category.

Classrooms with engineering. Participants who were placed in classrooms that incorporated engineering in some capacity (at either PBEA or EA) for at least one academic quarter included the following: prospective teachers Zeb, Xandra, Saul, Ralph, Nick, Monty, Carlos, and Anthony; preservice teachers Caitlyn, Kayla, and Haylee; and practicing teachers Ken, Kurt, Dana, Josh, Kristy, and Macy. The complexity of understanding of engineering design ranged unevenly. Some participants' understanding had a fairly low complexity, being classified into only two conceptual categories—in the case of Saul, Ralph, Nick, Carlos, and Anthony—while others demonstrated more complex understandings, being classified into four categories—in the case of Monty, Kayla, Haylee, Kurt, Dana, Josh, and Macy—five categories—in the case of Ken and Kristy—or all six conceptual categories—in the case of Zeb and Xandra.

Of the participants who demonstrated a lower complexity of understanding, all of them were classified in either the *Improvement* or *Business or Product Focused* conceptual categories. This might indicate that these participants who were in more engineering-focused contexts tended to have a more limited view of engineering design as either business or product driven, or as a process of constant improvement. Of the participants in engineering-focused contexts who demonstrated a more complex understanding of engineering design, they were more likely than participants in the science-only classroom context to discuss engineering design as a creative endeavor—indicated by discussing enough aspects of engineering design to be classified into the *Creative Thinking* conceptual category—with all five of the five total participants to be classified into this category. While this was the case for prospective and practicing teachers in engineering-focused classrooms, preservice teachers in these classrooms who had more complex understandings of engineering design tended to view engineering design as human oriented—indicated by their classification into the *Human Centered* category—and as being based on knowledge and skills of the engineer—indicated by their classification into the *Knowledge and Skills* category.

Findings by Demographic Information

Participants' demographic information was collected systematically for both prospective and preservice teachers, and included their gender, ethnicity, and undergraduate major. Demographic information for practicing teachers and teacher educators were not collected in a systematic way, however, gender and ethnicity could be collected, and some practicing teachers and teacher educators volunteered their undergraduate major during their focus group interviews or in follow-up discussion. This information was used to compare participants by each type of demographic information applicable to see if patterns among their views of engineering design emerged (see Table 4n).

Table 4n

Participants' Conceptual Category Classification by Demographic Information

Group	**Participant**	**Conceptual Category****	**Demographic Information**		
			Gender	*Ethnicity*	*Major*
Prospective	Zeb	🟦🟪🟩🟧🟥🟨	M	European American	Physics
Prospective	Xandra	🟦🟪🟩🟧🟥🟨	F	Latino/a	Physics
Prospective	Saul	🟦🟩	M	Asian American	Physics
Prospective	Rick	🟦🟧	M	Latino/a	Chemistry
Prospective	Ralph	🟦🟪	M	Asian American	Electrical Engineering
Prospective	Nick	🟦🟪	M	European American	Biochemistry
Prospective	Monty	🟦🟪🟥🟨	F	European American	Chemistry
Prospective	Carlos	🟦🟩	M	European American	Physics
Prospective	Anthony	🟦🟪	M	European American	Physics
Preservice	Molly	🟦🟪	F	European American	Biology
Preservice	Kari	🟦🟧🟨	F	European American	Anthropology
Preservice	Adam	🟦🟩🟧	M	European American	Biology
Preservice	Caitlyn	🟦🟪	F	European American	Engineering Physics
Preservice	Sasha	🟦🟪🟧🟨	F	European American	Computer Science
Preservice	Kayla	🟦🟪🟧🟨	F	European American	Physics
Preservice	Haylee	🟦🟩🟧🟨	F	European American	Physics
Preservice	David	🟦🟪	M	Asian American	Biology
Practicing	Ken	🟦🟪🟩🟧🟥	M	European American	Physics
Practicing	Kurt	🟦🟪🟩🟧	M	European American	Electrical Engineering
Practicing	Dana	🟦🟪🟩🟧	F	European American	Chemistry
Practicing	Josh	🟦🟪🟩🟧	M	European American	--
Practicing	Kristy	🟦🟪🟩🟧🟥	F	European American	--
Practicing	Macy	🟦🟪🟧🟨	F	European American	Physics
Practicing	Sandra	🟦🟪🟧🟨	F	European American	--
Educators	Sally	🟦🟧	F	European American	Biology
Educators	Patty	🟦	F	European American	Environmental Science
Educators	Jasmine	🟦🟧	F	European American	Biology

-- indicates that participants were not asked for or did not volunteer this demographic information

**Blue = Basic NGSS; Purple = Improvement; Green = Business or Product Focused; Orange = Knowledge & Skills; Red = Creating Thinking; and Yellow = Human Centered

Gender. Participants were divided relatively equally between males (12 total) and females (15 total), with more prospective teachers being males than females (7 compared to 2), more preservice teachers being females than males (6 compared to 2), relatively equal numbers of male and female practicing teachers (3 males and 4 females), and all teacher educators (3 total) being female. Overall, the main difference between the participants based on gender was the tendency for female participants, especially those with a more complex understanding of engineering design, to recognize the fact that engineering design is human oriented and involves collaborating and/or thinking about the user. This is indicated by the fact that many more female participants were classified into the *Human Centered* conceptual category than male participants (8 females to 1 male).

Ethnicity. All participants were designated into one of three major ethnic groups: Latino/a, Asian American, and European American. A majority of participants (22) were European American, three participants were Asian American, and two participants were Latino/a. Overall, there did not appear to be any distinctions between the views or understandings of engineering design and ethnic group. This might be, in part, because the groups for Latino/a and Asian American participants were quite small.

Academic major. Prospective and preservice teacher participants were asked about their undergraduate major before enrolling in either the internship program or the teacher education program. The internship program that prospective teachers were a part of required them to be physical science (physics or chemistry) or engineering related majors. Four practicing teachers volunteered their undergraduate major during their focus group interviews and the three teacher educators’ undergraduate majors were collected in follow-up discussion with them. Four participants had engineering related majors, nine were physics majors, four were chemistry majors, and seven had biology related majors. The findings of these 24 participants’ views and understandings of engineering design broken out by the type of academic major is discussed below.

Engineering related. Contrary to what would commonly be theorized, participants who had engineering related majors were not those with the most complex understandings of engineering design. Participants with these types of majors either had a low—indicated by being classified into only two conceptual categories, like Ralph and Caitlyn—or moderate complexity of understanding—indicated by being classified into four conceptual categories, like Sasha and Kurt. Participants with the lower complexity of understanding were classified into the *Improvement* category and viewed engineering design as a process of constant improvement. Those with more complex understanding were classified into the *Knowledge and Skills* category and viewed engineering as being based on the knowledge and skills of the engineer.

Physics. The largest number of participants (9) were physics majors and they also have the widest range of complexity of understanding. Three participants—Saul, Carlos, and David—were only classified into two conceptual categories, with two in the *Business or Product Focused* category and the other in the *Improvement* category. Three participants—Kayla, Haylee, and Macy—were classified into four conceptual categories, indicating a moderate complexity of understanding, with all of them being classified into the *Knowledge and Skills* and *Human Centered* categories. This might indicate that they viewed engineering design as being based on thinking about the user, collaboration, and using one's knowledge and skills. One participant—Ken—was classified into five categories, all except the *Human Centered* category, and two participants—Zeb and Xandra—demonstrated integrated understanding by being classified into all six conceptual categories. This is important to note because they were the only two participants who demonstrated an integrated understanding of engineering design at any instance across the data, and they were both physics majors in addition to both being prospective teachers.

Chemistry. Three prospective teachers and one practicing teacher were chemistry majors. Two participants—Rick and Nick—demonstrated a lower complexity of understanding by being classified into only two conceptual categories. However, Rick was in the *Knowledge and Skills* category, indicating a view of engineering design as being based on knowledge and skills of the engineer, whereas Nick was in the *Improvement* category, indicating a view of engineering design as a process of constant improvement.

The other two participants—Monty and Dana—demonstrated a moderate complexity of understanding by being classified into four conceptual categories. However, they too had varying views of engineering design, although they both have the *Improvement* category in common. Monty viewed engineering design as more of a creative and human oriented endeavor (indicated by being classified in the *Creative Thinking* and *Human Centered* categories), whereas Dana viewed it as more business and product focused and based on knowledge and skills of the engineer (indicated by being classified in the *Business or Product Focused* and *Knowledge and Skills c*ategories).

Biology related. Seven participants had biology related majors, and overall had a lower complexity of understanding of engineering design. A teacher educator, Patty, demonstrated the lowest complexity of understanding of engineering design, only being classified into the *Basic NGSS* category. She is also the only participant who was an environmental science major. Four participants—Molly, David, Sally, and Jasmine—demonstrated a low complexity of understanding of engineering design, being classified into only two conceptual categories. Two of these participants (Molly and David) were classified into the *Improvement* category, which indicates that they viewed engineering design as the process of constant improvement, whereas Sally and Jasmine (the two teacher educators) were classified into the *Knowledge and Skills* category, indicating that they viewed engineering design as being based on the knowledge and skills of the engineer.

The two other participants—Kari and Adam—demonstrated a relatively low to moderate complexity of understanding of engineering design, indicated by being classified into three conceptual categories. Both of them were classified in the *Knowledge and Skills* category, indicating that they tended to view engineering design as based on the knowledge and skills of the engineer. Overall, the participants with biology related majors tended to have the lowest complexity of understanding as a group compared to the other types of majors, whereas the group of participants with physics majors included those with the most complex understandings.

Chapter 5: Discussion

I conclude this study by first proving a summary of the main findings. Next, I discuss the potential implications and limitation of this study. Finally, I explore future directions for research.

Summary of Findings

Through level 1 analyses, I constructed a comprehensive list of 30 aspects of engineering design (see Table 5a). Some of these aspects of engineering design were taken from the *Next Generation Science Standards* (NGSS Lead States, 2013); some, from a review of literature on engineering design; and some, from the data themselves. It is important to emphasize that all aspects were present in the data. The most common aspects of engineering design that were discussed across participants tended to be those included in the *Next Generation Science Standards* (NGSS Lead States, 2013), except for *physical object*, which was added during coding.

These commonly discussed aspects of engineering design exemplify the basic process of engineering that is done to create something (e.g. a physical object): A problem is identified, constraints are considered, and designs are tested and evaluated iteratively before creating something. Many participants also discussed the process of developing engineering solutions by brainstorming and researching solutions and using creativity (usually to develop novel solutions). After solutions are generated, participants discussed the need to compare solutions to find the best to move forward with and then to communicate their design either through writing, talking, or creating drawings or models of it. Finally, participants noted the importance of creating an optimal design that solves the engineering problem best, usually in the form of a final product.

Table 5a

Identified Aspects of Engineering Design by Source

Source	**Identified Aspect**
1. **NGSS Component 1** *Defining and delimiting engineering problems*	Problem or need Thinking about the user Research Identifying constraints The scope of design Subproblems
2. **NGSS Component 2** *Designing solutions to engineering problems*	Communication Developing solutions Research
3. **NGSS Component 3** *Optimizing the design solution*	Comparing solutions Secondary effects Design process Testing and evaluating Optimal design
Added Aspects— *From Review of Literature*	Competition Prior knowledge and experience Based on Science Creativity Aesthetics Simplicity Collaboration Evolutionary design Final product Never ending process
Added Aspect— *From Coding of Data*	Using technology Physical object Inspiration Using mathematics Engineering is integrated Thinking like an engineer

One participant, Xandra, discussed the most (eight) aspects of engineering design at a high frequency. Several of these aspects are also in line with the *NGSS* description of engineering design (*problem or need, identifying constraints, developing solutions,* and *testing and evaluating*), however, some indicated a more sophisticated understanding.

Xandra recognized the need to use science and technology throughout the engineering design process, and viewed collaboration and the sharing of knowledge and experience as important. She also understood the importance of thinking about the user when designing solutions, an important aspect of engineering in the business world.

Table 5b

Conceptual Categories of Engineering Design

Conceptual Category	Criteria for Inclusion	Description
Basic NGSS	Inclusion in this category requires that participants discuss at least 3 of the following aspects of engineering design: 1) Define a problem or need 2) Identify constraints 3) Develop solutions 4) Optimizing the solution 5) The iterative design process	This category includes references to the aspects of engineering design that are included in the basic description of engineering design provided in the *Next Generation Science Standards* (NGSS Lead States, 2013).
Business or Product Focused	Inclusion in this category requires that participants discuss at least 4 of the following aspects of engineering design: 1) Identifying constraints 2) The scope of design 3) Subproblems 4) Competition 5) Simplicity 6) Final product 7) Physical object	This category relates to a business or product focused view of engineering design because they highlight the importance of working within the constraints and scope of the engineering project-at-hand and breaking down the project into smaller, more manageable goals. There is also a focus on creating a physical object or final product that is the simplest or most efficient and is better than the competition's.
Knowledge & Skills	Inclusion in this category requires that participants discuss at least 4 of the following aspects of engineering design: 1) Research the problem 2) Research solutions 3) Prior knowledge and experience 4) Based on science 5) Engineering is integrated 6) Using mathematics 7) Using technology	This category relates to using one's knowledge and skills in engineering design because they highlight how one needs to utilize prior knowledge and skills (from various areas including science, mathematics, technology, or other subject) or seek more knowledge and skill (usually through research) through the engineering design process.

Creative Thinking	Inclusion in this category requires that participants discuss at least 3 of the following aspects of engineering design: 1) Aesthetics 2) Creativity 3) Inspiration 4) Thinking like an engineer	This category relates to thinking in a way that allows one to solve problems creatively by generating innovative ideas that draw on one's creative and artistic skills.
Human Centered	Inclusion in this category requires that participants discuss at least 3 of the following aspects of engineering design: 1) Thinking about the user 2) Communication 3) Secondary effects 4) Collaboration	This category of engineering design highlights the human element of engineering design, which includes the need to think about how the design process involves working with and communicating with others and how the product should consider people (either through personal use or as an effect of others' use).
Improvement	Inclusion in this category requires that participants discuss at least 3 of the following aspects of engineering design: 1) Comparing solutions 2) Optimal design 3) Testing and evaluation 4) Evolutionary design 5) Never ending process	This category of engineering design highlight the desire to improve engineering solutions through constantly testing, comparing and evaluating them.

Aspects of engineering design that were discussed by few participants were those that focused on the things engineers must take into consideration when designing, including the scope of the design, aesthetics, simplicity or efficiency of the design, secondary effects of using the design or product, and aspects of competition like creating a better solution than others. These aspects also included how engineers think in a certain way (e.g., problem solving, etc.) and often rely on inspiration or an idea, rather than first identifying a problem or need. Last, these aspects recognize how engineering can integrate multiple fields (more than just science) and that often engineers build on the designs of others to just make small, iterative changes (*evolutionary design*).

Through level 2 analyses, the aspects of engineering design were grouped in meaningful ways to create common conceptual categories of engineering design that participants could be classified into based on their discussions (see Table 5b). Criteria for inclusion into each of these categories was established, and participants were sorted into all the conceptual categories that their discussion in an interview and/or associated concept map permitted.

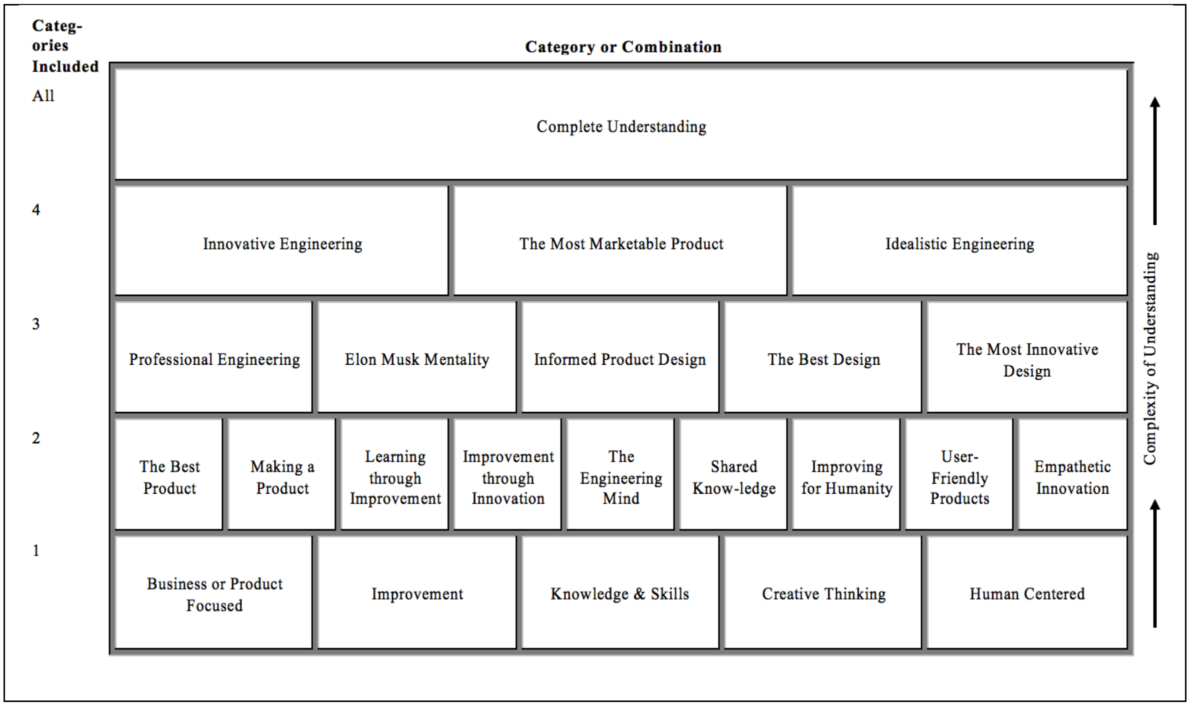


Figure 5a. Levels of conceptual categories by complexity of understanding of engineering design

Some participants were classified into multiple conceptual categories at a given instance, which indicated that they had a more complex understanding of engineering design. The more conceptual categories that a participant was classified into, the more complex their understanding (see Figure 5a). Each of these combinations were described and participants were mapped by instance to where they fit. The conceptual categories that participants were classified into gives a picture of their view of engineering design, where the number of categories they were classified into indicated their complexity of understanding of engineering design.

Finally, in level 3 analyses, the conceptual categories participants were classified into were compared to their experience, context, and demographics. Findings for prospective and preservice teachers over time were discussed first. Some prospective and preservice teachers appeared to gain a more complex understanding of engineering design over time throughout the study year, indicated by an increase in the number of conceptual categories they were classified into a later instances in the data. Some prospective and preservice teachers had a decrease in their understanding of engineering design, as indicated by a decrease of the number of conceptual categories that they were classified into at a given instance over time. Some prospective and preservice teachers had either their lowest of highest complexity of understanding midway through the study year (in either their post-summer or winter interviews). There were no distinct patterns that indicated a definite trend in their complexity of understanding over time.

Next, findings were discussed by where participants fell along the learning-to-teach continuum (prospective teacher, preservice teacher, practicing teacher, or teacher educator). The prospective teacher participants were classified into an average of 2.33 major conceptual categories for engineering design in their final interviews and with a range of one to five categories. Preservice teachers were classified into an average of 1.88 major conceptual categories in their final interviews with a range of one to three categories. Practicing teachers had an average of 3.29 major conceptual categories with a range of three to four categories, and finally, teacher educators were classified into an average of 0.67 major categories with a range of zero to one category.

Prospective teachers were the only group to have participants (two total) classified into all of the conceptual categories for engineering design—demonstrating an integrated understanding. This group (along with the practicing teacher group) included the only participants to be classified into the *Creative Thinking* category, with the highest percentage of participants in this category than any other group. Overall, this group had a wide variety of conceptual categories that participants were classified into and a fairly even distribution of participants in each.

The practicing teacher group was the only group that had all participants be classified into both the *Improvement* and *Knowledge and Skills* categories, and had two participants be classified in five of the six identified conceptual categories. This indicates that not only do these practicing teachers have a complex understanding of engineering design, they also represent a wide range of views of engineering design that span all conceptual categories established across the data. The preservice teachers were less likely than the prospective and practicing teachers to view engineering design as business or product-driven. The teacher educator group had the least complex view of engineering design and had the lowest number of conceptual categories represented by participants. Teacher educators are more likely to view engineering design as being based on knowledge and skills, however their primary view of engineering design was based on the basic description provided in the *Next Generation Science Standards* (NGSS Lead States, 2013).

Findings by participants' prior experience with engineering were also discussed. The overall trend was an increase in complexity of understanding as the participant's prior experience with engineering increased. Prior experience with engineering might have a loose association with the complexity of understanding of participants, although this was not a clear pattern because the variation among participants was so large. Some prior experiences with engineering might inform participants' likelihood to have certain views or understanding of engineering design. Participants who had formal engineering experience in the form of engineering courses, research, or being a professional engineer tended to have views of engineering design more in line with the *Human Centered* and *Business or Product Focused* conceptual categories. Also, those who had experience doing professional engineering or engineering research had a more complex understanding of engineering design.

Findings by participants' classroom placements were also discussed depending on whether the placement incorporated engineering. For participants in science only classrooms, their complexity of understanding of engineering design had a small range; it was not too wide to conclude that participants who were in science-only classes tended to have a moderate complexity of understanding of engineering design – with no participants too low, or too high. There were also no participants in these types of classrooms who discussed aspects of engineering design that classified them into the *Creative Thinking* category, and only one was classified into the *Business or Product Focused* category.

The complexity of understanding of engineering design ranged unevenly among participants who were placed in classrooms with an engineering component. They either demonstrated a fairly low complexity of understanding or a fairly high complexity of understanding. Of the participants in engineering-focused contexts who demonstrated a more complex understanding of engineering design, they were more likely than participants in the science-only classroom context to discuss engineering design as a creative endeavor (*Creative Thinking*).

Last, findings by participants' demographic information were discussed, including gender, ethnicity, and academic major. Male participants with a moderately complex understanding of engineering design tended to view engineering as being business or product oriented and based on the knowledge and skills of the engineer. Zeb was the only male participant who recognized the human element in engineering design by being classified in the *Human Centered* conceptual category. Female participants with a moderate complexity of understanding were more likely to view engineering design as being based on the knowledge and skills of the engineer. They were more likely than male participants to view engineering as a human oriented endeavor, and were not as likely to view it as being business or product oriented. Overall, the main difference between the participants based on gender was the tendency for female participants, especially those with a more complex understanding of engineering design, to recognize the fact that engineering design is human oriented and involves collaborating and/or thinking about the user. This was indicated by the fact that many more female participants were classified into the *Human Centered* conceptual category than male participants.

There did not appear to be any distinctions between the views or understandings of engineering design by ethnic group of participants. This might be, in part, because the groups for Latino/a and Asian American participants were quite small.

Finally, participants in engineering related undergraduate majors either had a low or moderate complexity of understanding, and participants in biology related majors had a low complexity of understanding of engineering design. The group of participants who were physics undergraduate majors, in contrast, contained the only two participants who ever demonstrated an integrated understanding of engineering design at any instance across the data.

Implications

This study has the potential for a wide reach in the education world. The incorporation of engineering design in the *Next Generation Science Standards* (NGSS Lead States, 2013) shows that there is now a national platform where the implications of teaching and researching engineering design are considered. First, in this study, the way the *NGSS* describes engineering design was found to be incomplete. I was able to identify many additional aspects of engineering design that were not present in the *NGSS*; these additional aspects emerged from a review of literature on engineering design and from examining participants' descriptions. While the *NGSS* lists only three major components for engineering design, this study identified a total of 30 smaller aspects of engineering design important for engaging in the process of engineering.

The wide range of views and conceptions of engineering design that were discovered from these many identified aspects provides a broader range of possibilities for how individuals may view engineering. It is promising that such a wide variety of views exists and is present in the population along the learning-to-teach continuum, since explaining the variety of things that engineering encompasses and what engineers do is cited as a grand challenge to engineering education (Sneider, 2016). This study showed that teachers and teacher educators do not just view engineers as either mechanics or brilliant engineers at MIT. Rather, participants discussed a wide variety of aspects of engineering design which could be integrated together to create multiple, more nuanced conceptions.

To continue, the development of several levels of conceptual categories of engineering design created a meaningful way to examine the views and understandings of participants. The basis for creating these conceptual categories was founded on the methodology of phenomenography (Marton, 1981). This method provided a concrete way to sift through all the data and find meaning in the various ways that participants discussed the focal concept—engineering design. Once six main categories were established, it was recognized that the views and understanding of participants could gain complexity as these categories were combined.

This work allows one to identify a view (or views) of engineering design that an individual may hold and use that information to determine how complex their overall understanding may be. This creates opportunities to find commonalities in local or larger contexts among views and understandings of engineering design, and prvides opportunities for improvement through professional development or more education and experiences in engineering. In fact, Sneider (2016) cited that teaching teachers and teacher educators about how to incorporate engineering into science instruction (as is required by the *NGSS;* NGSS Lead States, 2013) is another grand challenge to engineering education.

The fact that participants across the learning-to-teach continuum demonstrated such a wide range of views and understandings of engineering design suggested that these views and understandings are more likely to be shaped through their life depending on their experiences and beliefs, and not just as a result of their time in the classroom. This is shown by the fact that those with the most classroom engineering experience did not necessarily have the most complex understandings of engineering design, and those with little classroom experience did. This highlights that educators at all levels hold varied understandings of engineering design – that understandings of engineering design vary from person to person, with no single group having a better understanding overall. This means that both teachers and teacher educators need to be educated about engineering design. Perhaps they can be provided with more authentic engineering experiences or partnerships with professional engineers—which was found to produce individuals with more complex understandings in this study.

Goldman and Zielezinski (2016) provided a concrete set of steps for learning “design thinking” in K-12 and methods for teaching teachers about how to incorporate engineering design into their science instruction (through the *NGSS;* NGSS Lead States, 2013) as well as their English language arts and mathematics instruction (through the *Common Core State Standards;* National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010a; 2010b; 2010c). They explained that the partnerships they had created with a teacher education program and a state office of education had allowed them to immerse teachers in learning about engineering design. If these kinds of partnerships are leveraged and more insightful information on teacher knowledge of engineering design are gathered, more successful professional development experiences can be had.

Limitations

One major limitation of this study was the participants who were included. The prospective teacher participants were all part of an engineering-focused internship experience and were all physical science or engineering related majors. This population is not necessarily representative of the types of undergraduates who tend to go on to enroll in teacher education programs and was intentionally skewed based on the demands of the grant for the internship. While the preservice teacher group was likely more of a typical representation of the kinds of individuals who are in teacher education programs for secondary science, they were not ethnically diverse. The practicing teacher participants were part of the engineering-focused internship as well and were therefore much more familiar with engineering than the typical secondary science teacher. Because of this, the findings provide a much more optimistic picture of what practicing teachers know about engineering, but this is most likely not the case in most schools across the country. Last, the teacher educators were a small group of individuals from only one university teacher education program. Their findings are not representative of all secondary science teacher educators. Also, all three had science backgrounds and did not have much experience or education in engineering. Since the *NGSS* is still new in the science education world, these teacher educators were learning about engineering design alongside the preservice and practicing teachers they worked with.

There were also limitations in the methods used for this study. While the prospective and preservice teachers were interviewed at multiple times throughout the study year and completed at least two of their own concept maps of engineering design, this was not the case for the practicing teachers and teacher educators. Instead, they only participated in a single focus group interview and analyzed two example concept maps created by prospective teachers (rather than constructing their own). Because these two groups were not interviewed at multiple times throughout the study year, and did not complete their own concept map for engineering design, this might have limited their possible discussion and reflection on engineering that the prospective and preservice teachers were afforded. In addition, because the specific aspects and conceptual categories for engineering design were not established until data collection was complete, aspects and categories for engineering design could not be specifically probed for during interviews with participants. This, along with the variation in the types and frequency in interviews among participant groups, might have limited the opportunities for participants to discuss all aspects they understood to be part of engineering design, and thus, have limited the number of categories they identified.

While the aspects and conceptual categories for engineering design established in this study provide a fairly comprehensive picture of the breadth of understanding and views of engineering design for these groups of participants, they might not be applicable to the teaching population as a whole. Depending on the local contexts and the personal experiences of individuals, other aspects of conceptual categories of engineering design may emerge. As indicated by the pages of definitions of design that Archer (1968) provided, there are almost limitless ways that engineering design can be described. With technology and the engineering fields ever-expanding and growing ever-more complicated, this trend shows no sign of slowing down.

Future Directions

As the *Next Generation Science Standards* (NGSS Lead States, 2013) are implemented in more classrooms across the country, a larger study on the views and understandings of engineering design would provide valuable insight into what science teachers, in general, understand about this construct, would allow more nuanced comparisons within and across the learning-to-teach continuum, and would provide further insights into the strength and limitations of the model described in the standards. If a more streamlined approach to answer these research questions—that did not involve multiple one-on-one interviews, but perhaps open-ended survey questions instead—was implemented widely, patterns in teachers' views and complexity of understanding of engineering design could emerge.

With a larger sample, some of the factors that I compared in my study, which did not yield many differences across participants—such as ethnicity or academic major—could have the potential to show differences. I would be interested to further investigate individuals who have more formal engineering experience—in the form of an undergraduate major and/or a professional engineering position—to determine how these kinds of formal engineering experiences influence understandings and views of engineering design. In addition, if a larger sample is used, more sophisticated statistical analyses (such as latent class analysis; Dayton, 1998; Harlow, Nylund-Gibson, Iveland, & Taylor, 2013) could be used to more accurately group participants into each conceptual category for engineering design.

Furthermore, I think that expanding this kind of study to include elementary school teachers would also be beneficial. The *Next Generation Science Standards* (NGSS Lead States, 2013) includes engineering design in all grades from kindergarten through grade twelve. It is thought that because many elementary school teachers do not have much, if any, science background there is historically a lack of science being taught at the elementary school level (Schoeneberger & Russell 1986). Riggs and Enochs (1990) developed an instrument to look at the self-efficacy of elementary teachers towards teaching science, and others have found a relationship between the background of elementary teachers and their perceived adequacy to teach science (Jarrett, 1999). Because elementary school teachers have established roadblocks to teaching science, it is hard to believe that they will teach engineering now that it has been added to the elementary science standards. A systematic study on the views and understandings of elementary school teachers on engineering design may highlight common misconceptions that they hold, misalignments with the *NGSS* description of engineering design (especially for the elementary grade bands), and areas for improvement by professional development projects and formal education contexts to increase the experiences these teachers may have with doing engineering or with professional engineers. By expanding this work into the elementary grades, the potential findings of teachers along the learning-to-teach continuum would include those throughout K-12 education, potentially nationwide.

In sum, the country is at a turning point in science education, with the widespread implementation of the *NGSS*. Gaining a clearer understanding of teachers' views of one of the major components of these standards, engineering design, is crucial.

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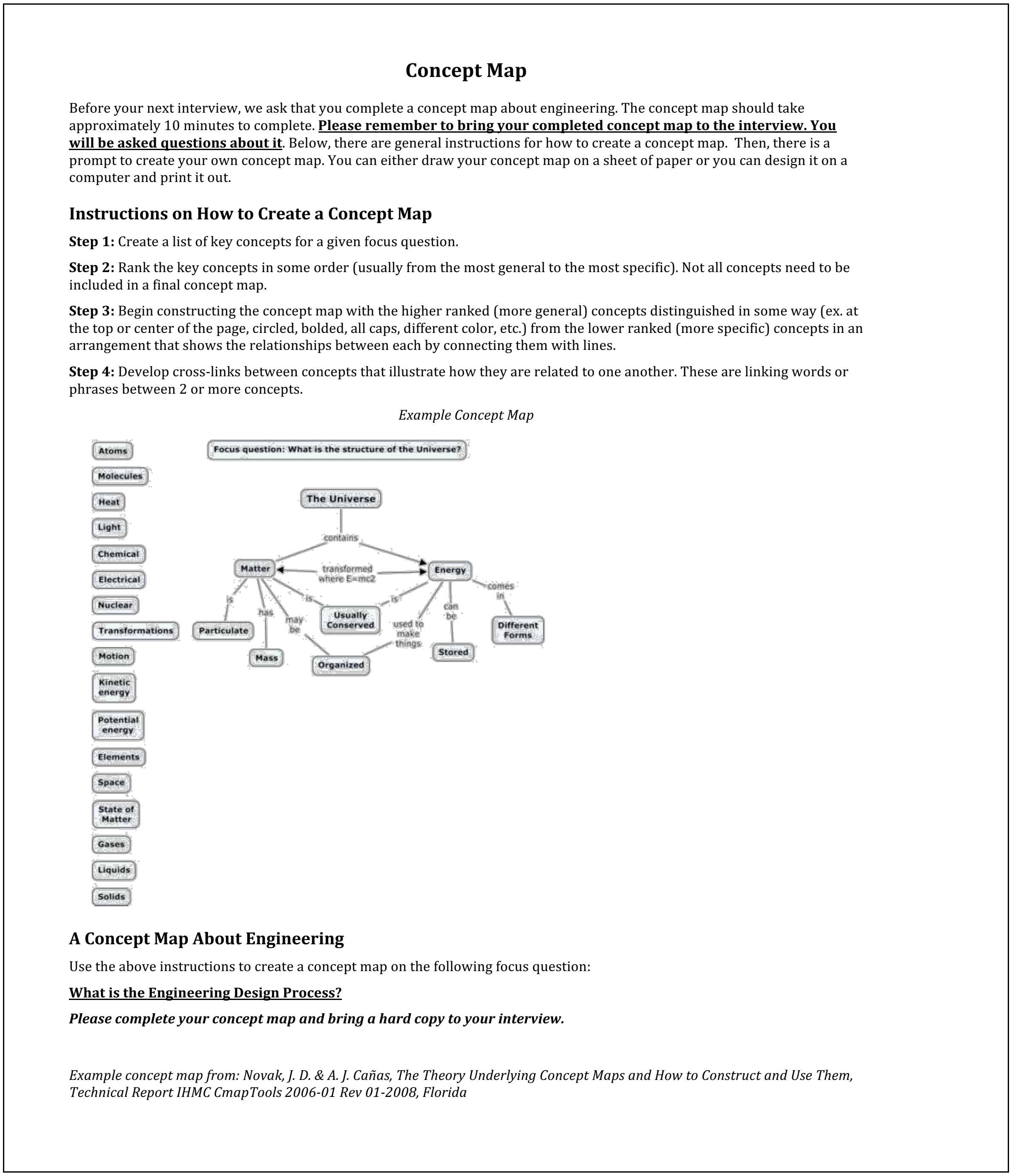
Appendices

Appendix A: Concept Maps



Concept Map

Before your next interview, we ask that you complete a concept map about engineering. The concept map should take approximately 10 minutes to complete. **Please remember to bring your completed concept map to the interview. You will be asked questions about it**. Below, there are general instructions for how to create a concept map. Then, there is a prompt to create your own concept map. You can either draw your concept map on a sheet of paper or you can design it on a computer and print it out.

Instructions on How to Create a Concept Map

Step 1: Create a list of key concepts for a given focus question.

Step 2: Rank the key concepts in some order (usually from the most general to the most specific). Not all concepts need to be included in a final concept map.

Step 3: Begin constructing the concept map with the higher ranked (more general) concepts distinguished in some way (ex. at the top or center of the page, circled, bolded, all caps, different color, etc.) from the lower ranked (more specific) concepts in an arrangement that shows the relationships between each by connecting them with lines.

Step 4: Develop cross-links between concepts that illustrate how they are related to one another. These are linking words or phrases between 2 or more concepts.

Example Concept Map

A Concept Map About Engineering

Use the above instructions to create a concept map on the following focus question:

What is the Engineering Design Process?

Please complete your concept map and bring a hard copy to your interview.

Example concept map from: Novak, J. D. & A. J. Cañas, The Theory Underlying Concept Maps and How to Construct and Use Them, Technical Report IHMC CmapTools 2006-01 Rev 01-2008, Florida

Figure A1. Instructions for creating concept maps (based on Novak & Canas, 2008)

Figure A2. *Example concept map #1*

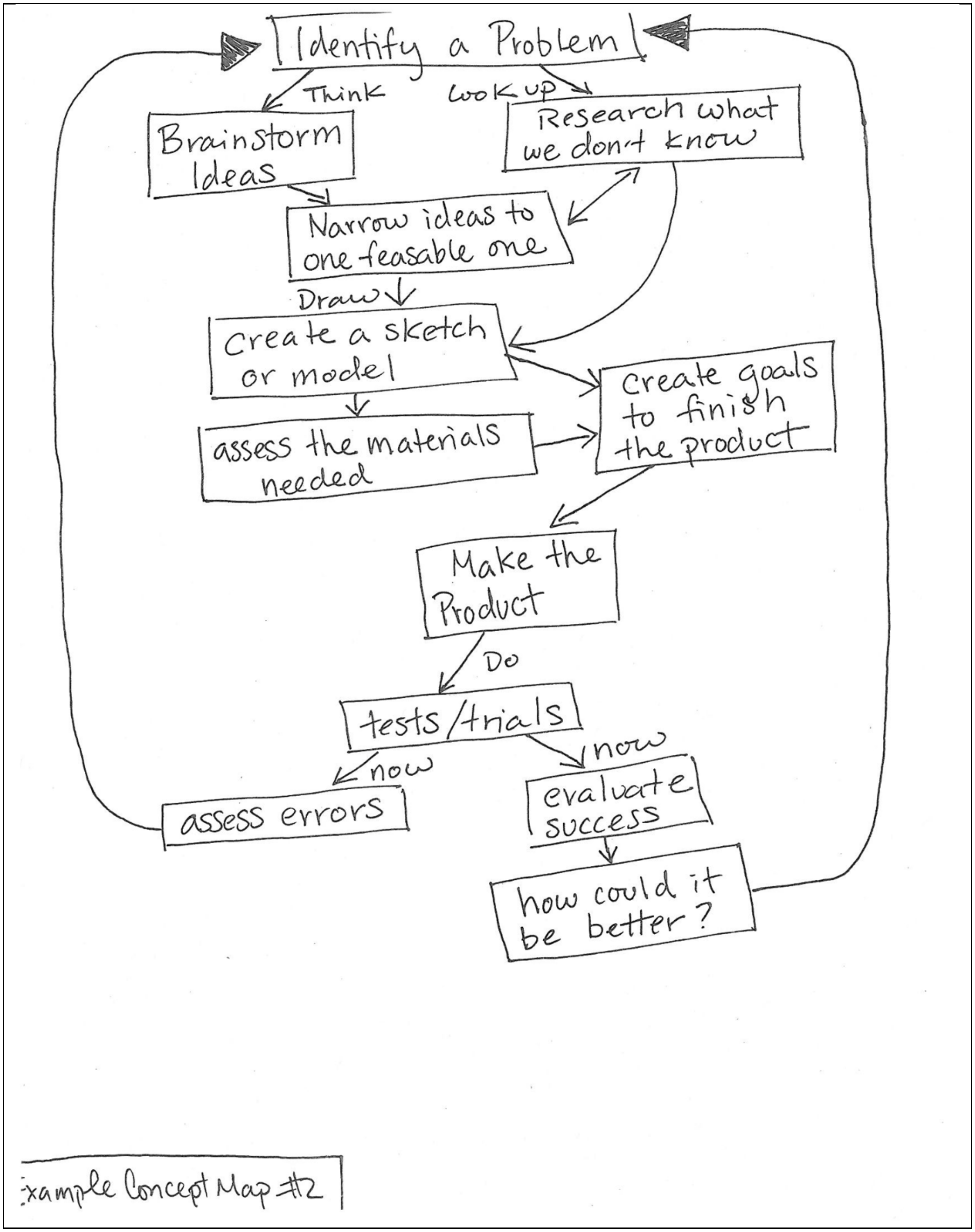


Figure A3. *Example concept map #2*

Appendix B: Interview Protocols

Prospective Teachers

[redacted] PRE Undergraduate Intern Interview Protocol
August 2015

Thank you for agreeing to be interviewed today. The purpose of this interview is to understand your thoughts on science and engineering teaching and learning. We are hoping to determine how this internship may influence these understandings. We ask that you try to be as candid and as specific as possible.

If there is a question you do not wish to answer, you can ask that it be skipped. If you later wish to revise an answer or to ask that an answer be deleted, you are free to do so as well.

We expect the interview to last about 45 minutes. It is divided into five parts. Do I have your permission to begin recording the interview?

<u>Background Information</u>

I'd like to ask you a few background questions about your interest in, and experiences with K-12 education.

1. Tell me about your reasons for becoming a [redacted] intern. What kinds of things do you want to learn about teaching in high-need schools?

2. What kinds of previous experiences do you have working with K-12 students in science and/or engineering? What kinds of science were you and these students engaged in? What kinds of engineering were you and these students engaged in?

3. Are you part of the [redacted] program? If yes, please describe the ways in which you feel you were prepared to teach underserved students.

4. Tell me about any other experiences you have working with K-12 students?

<u>Effective Science and/or Engineering Instruction</u>

These next few questions are about your ideas of effective science and engineering teaching and learning.

5. How do you define effective science and/or engineering teaching?

6. How do you think students best learn science and/or engineering?

7. What do you expect to learn about *teaching* science and/or engineering from the students you will work with?

8. What do you expect to learn about *how students learn* science and/or engineering from the students you are about to work with?

Specific Aspects of Science Instruction Part 1

These next few questions are about a specific aspect of science and engineering instruction: the practices.

9. Have you heard about the Next Generations Science Standards? Please tell me what you know. [If haven't heard, briefly explain to them.]

10. Here are cards with the eight science and engineering practices listed on them.

    a. Which ones have you seen implemented either in your own educational experience or in one you have observed. How were they implemented?
    b. Which **one** do you think most important to teach students? Why?
    c. Which **one** do you think you need more help to understand? What questions do you have?

Specific Aspects of Science Instruction Part 2

This next set of questions is about engineering.

11. What previous experience do you have with engineering? (e.g., engineering courses have you taken at either the high school or university level, doing engineering in an informal educational setting, etc.)

12. Do you know anyone who is an engineer? What is their relationship to you and what kind of engineering do they do?

13. Please describe what you think engineering is.

    a. Probe: (If yes to #11) What have you learned about engineering from the **engineering** courses you have taken?
    b. Probe: What have you learned about engineering from the **education** courses you have taken? (e.g., [redacted] courses, other courses about education?… NGSS or Framework engineering components, Engineering Design, etc.)
    c. Probe: In what ways is "doing" engineering different from "doing" science or mathematics?

11. You drew a concept map that demonstrated what you thought the engineering design process was.
    a. Can you briefly describe your concept map.
    b. Can you elaborate on **one** part of your concept map that you think is the most important. Why? Is this important for teaching engineering or for doing engineering?
    c. Which **one** part of your concept map do you think you need more help to understand? Why? Is this something you need help understanding for teaching engineering or for doing engineering?
    d. I would like to keep your concept map (make sure name/date of interview is on it).

12. How might you teach the engineering design process to high school students?

13. Can you describe a specific engineering lesson you might teach to a class of high school students? Probe: What do you think your students would learn about the engineering design process as a result?

<u>Future Plans</u>

In this last set of questions, I'd like to ask about your career plans.

14. What is your current career path? Would you consider teaching? Why or why not?

15. What are you plans for this academic year? What other courses do you plan to take? Do you plan to pursue the Undergraduate Minor in Science and Mathematics Education?

<u>Wrap-Up</u>

16. What questions do you have for me going into this experience?

Thanks!

Figure B1. Initial interview protocol for prospective teachers

[redacted] POST Undergraduate Intern Interview Protocol

September 2015

Thank you for agreeing to be interviewed today. The purpose of this interview is to understand your thoughts on science and engineering teaching and learning. We are hoping to determine how this internship may have influenced these understandings. We ask that you try to be as candid and specific as possible.

If there is a question you do not wish to answer, you can ask that it be skipped. If you later wish to revise an answer or to ask that an answer be deleted, you are free to do so as well.

We expect the interview to last about 45 minutes. It is divided into five parts. Do I have your permission to begin recording the interview?

I. Background Information

First, I'd like to ask you a few questions about your [redacted] experience.

1. Tell me about your [redacted] placement.
   [Probes: In what school and with what kinds of teachers and students have you worked this summer? What kinds of science and/or engineering were the students and teachers engaged in?]

2. What successes did you experience in your placement?

3. a. What challenges did you encounter?
   b. Why do you think such challenges happened?

4. What did you learn about *teaching* science and/or engineering during your placement?

5. What did you learn about *how students learn* science and/or engineering during your placement?

II. Science and/or Engineering Instruction

These next few questions are about your ideas about teaching and learning science and engineering.

6. How do you define effective science and/or engineering teaching?

7. How do you think students best learn science and/or engineering?

8. Here are the cards with the eight science and engineering practices from the *Next*

Generation Science Standards. First, please separate them into 2 piles: Those that you have seen implemented in your placement, and those that you have not seen implemented in your placement. Then I'll ask you some questions about them.

- a. *[For each practice the intern has seen implemented, ask:]*
  - i. How would you define this practice?
  - ii. How was this practice implemented? Please, give me some examples if possible.
- b. *[For each practice the intern did not see, ask:]*
  - i. How would you define this practice
- c. Out of all the practices:
  - i. Which **one** do you think is most important to teach students? Why?
  - ii. Which practices did you learn more about through [redacted]? What did you learn?
  - iii. Which ones do you think you need more help to understand?

III. Engineering Design

This next set of questions is specifically about engineering.

9. a. Please describe what you think engineering is.
   b. Has your understanding of engineering changed since you began this internship? If yes, how so?
   c. (If yes to #9b) What may have changed your view of engineering? The seminar sessions? The classroom experiences? Something else?

10. Have you noticed a difference in "doing" engineering and "doing" science during this internship experience? What are the differences you've seen?

11. How do you think engineering in the context of education is similar to or different from engineering in the field?

12. a. Do you consider yourself an engineer? Why or why not?
    b. Do you consider the teachers and/or students you have worked with in this internship engineers? Why or why not?

13. Here is the concept map you drew last week. This map demonstrates what you thought the engineering design process was.

    a. Can you describe your concept map in more detail? What do all of the connections you made mean to you?
    b. Which parts of your concept map came from your classroom experiences? Seminar session? Somewhere else?
    c. Can you elaborate on **one** part of your concept map that you think is the

most important? Why? Is this important for teaching engineering or for doing engineering?

d. Which **one** part of your concept map do you think you need more help to understand? Why? Is this something you need help understanding for teaching engineering or for doing engineering?

14. a. How might you teach the engineering design process to high school students?
    b. Can you describe a specific engineering lesson you might teach to a class of high school students? [Probe: What do you think your students would learn about the engineering design process as a result?]

IV. Future Plans [CAN BE SKIPPED IF SHORT ON TIME]

In this last set of questions, I'd like to ask about your career plans.

15. What is your current career path? Would you consider teaching? Why or why not?

16. What are your plans for this academic year? What other courses do you plan to take? Do you plan to pursue the [redacted]?

17. Do you plan to continue helping at [redacted] during the academic year? Why or why not?

V. Wrap-Up

18. How might your experiences in [redacted] be enhanced and improved? What suggestions do you have for this program?

19. Do you have any questions about the program for us?

Thanks!

Figure B2. Post-summer interview protocol for prospective teachers

[redacted] PRE Undergraduate Intern Interview Protocol

Winter 2016

Thank you for agreeing to be interviewed today. The purpose of this interview is to understand your thoughts on science and engineering teaching and learning. We are hoping to determine how this internship may influence these understandings. We ask that you try to be as candid and as specific as possible.

If there is a question you do not wish to answer, you can ask that it be skipped. If you later wish to revise an answer or to ask that an answer be deleted, you are free to do so as well.

We expect the interview to last about 30 minutes. It is divided into two parts. Do I have your permission to begin recording the interview?

Background Information

1. Did you continue to work in the classroom during Fall and/or Winter quarters?

    a. What influenced your decision to/not to continue to work in the classroom during the academic year?
    b. (if yes) In what ways is the experience during the academic year similar/different to your summer 5 week experience?
    c. (if yes) What successes and challenges have you experienced in the classroom during the academic year?

2. How have your experiences in this program influenced your feelings about teaching? Are you more or less likely to become a teacher after participation in this program?

Specific Aspects of Science Instruction

This next set of questions is about engineering. (If they didn't draw a concept map about the engineering design process ahead of time give them 5-10 minutes to do this now)

1. Please describe what you think engineering is.

    a. Has your understanding of engineering changed since you began this internship? If yes, how so?
    b. What may have changed your view of engineering?
    c. What have you learned about engineering from any courses you have taken? (engineering, education, or other courses)

2. In what ways is "doing" engineering different from "doing" science? Have you seen these differences in your experiences during this internship?

3. How do you think engineering in the context of education is similar to or different from engineering in the field?

4. Do you consider yourself an engineer? Why or why not?

5. Do you consider the teachers and/or students you have worked with in this internship engineers? Why or why not?

6. You drew a concept map that demonstrated what you thought the engineering design process was.
    a. Can you describe your concept map in more detail? What do all of the connections you made mean to you?
    b. Can you elaborate on **one** part of your concept map that you think is the most important. Why? Is this important for teaching engineering or for doing engineering?
    c. Which **one** part of your concept map do you think you need more help to understand? Why? Is this something you need help understanding for teaching engineering or for doing engineering?

7. How might you teach the engineering design process to high school students?

8. Can you describe a specific engineering lesson you might teach to a class of high school students? [Probe: What do you think your students would learn about the engineering design process as a result?]

Wrap-Up

9. What questions do you have for me?

Thanks!

Figure B3. Winter interview protocol for prospective teachers

[redacted] Final Undergraduate Intern Interview Protocol

Spring 2016

Thank you for agreeing to be interviewed today. The purpose of this interview is to understand your thoughts on science and engineering teaching and learning. We are hoping to determine how this internship may influence these understandings. We ask that you try to be as candid and as specific as possible.

If there is a question you do not wish to answer, you can ask that it be skipped. If you later wish to revise an answer or to ask that an answer be deleted, you are free to do so as well.

We expect the interview to last about 30 minutes. It is divided into four parts. Do I have your permission to begin recording the interview?

Background Information

3. Did you continue to work in the classroom during Winter and/or Spring quarters?

    a. What influenced your decision to/not to continue to work in the classroom during the academic year?
    b. (if yes) In what ways is the experience during the academic year similar/different to your summer 5 week experience?
    c. (if yes) What successes and challenges have you experienced in the classroom during the academic year?

4. How have your experiences in this program influenced your thoughts and feelings about teaching? Are you more or less likely to become a teacher after participation in this program?

Effective Science and/or Engineering Instruction

These next few questions ask about your ideas of effective science and engineering teaching and learning.

5. How do you define effective science and/or engineering teaching?

6. How do you think students best learn science and/or engineering?

7. What did you learn about *teaching* science and/or engineering from the teachers and students you worked with?

8. What did you learn about *how students learn* science and/or engineering from the teachers and students you worked with?

Specific Aspects of Science Instruction Part 1

This next set of questions is about a specific aspect of science and engineering instruction: the practices.

9. Please tell me what you know about the Next Generations Science Standards?

10. Here are cards with the eight science and engineering practices listed on them.

    a. Which ones have you seen implemented either in your own educational experience or in one you have observed? How were they implemented?
    b. Which **one** do you think most important to teach students? Why?
    c. Which **one** do you think you need more help to understand? What questions do you have?

Specific Aspects of Science Instruction

This final set of questions is about engineering specifically. (If they didn't draw a concept map about what they think the engineering design process looks like ahead of time, give them 5-10 minutes to do this now)

11. Please describe what you think engineering is.

    a. In what ways is "doing" engineering different from "doing" science?

    b. How do you think engineering in the context of education is similar to or different from engineering in the field?

    c. Do you think your understanding of engineering has changed since you began the [redacted] internship? If yes, how so?

    d. What have you learned about engineering since you began the [redacted] internship? How did you learn this? (e.g engineering/education classes, experiences, other?)

12. Do you consider yourself an engineer? Why or why not?

    a. Do you consider the students or teachers you have worked with throughout the [redacted] internship engineers? Why or why not?

13. Can you describe a specific engineering lesson you might teach to a class of high school students. Probe: What do you think your students would learn about the engineering design process as a result?

14. The next questions are about your concept map.

    a. Can you describe your concept map in more detail? What do all of the connections you made mean to you?

    b. Can you elaborate on one or more parts of your concept map that you think are the most important? Why? Are they important for teaching engineering or for doing engineering?

    c. Which part(s) of your concept map do you think you need more help to understand? Why? Is this something you need help understanding for teaching engineering or for doing engineering?

    d. I would like to keep this concept map (make sure you're name is on it).

<u>Wrap-Up</u>

15. When are you planning to graduate?
    a. If you are around next year, would you be interested in a [redacted] research position with our research team?

16. What questions do you have for me?

Thanks!

Figure B4. Final interview protocol for prospective teachers

Preservice Teachers

[redacted] Teacher Candidate Interview Protocol II
August 2015

Thank you for agreeing to be interviewed today. The purpose of this interview is to learn some of the successes and challenges you are experiencing as a teacher candidate. We are trying to redesign the methods courses in science and mathematics to better support beginning teacher learning. We ask that you try to be as candid and as specific as possible.

The information from this interview will not affect your course grades, your teaching placements, or your standing in the [redacted] Teacher Education Program. If there is a question you do not wish to answer, you can ask that it be skipped. If you later wish to revise an answer or to ask that an answer be deleted, you are free to do so as well.

We expect the interview to last about 30 minutes. It is divided into three parts. Do I have your permission to begin recording the interview?

Specific Aspects of Science and Mathematics Instruction Part 1

These next few questions are about language and literacy in science or mathematics instruction.

1. As you finish up/After your recent course on Foundations of Academic Language, tell me what you learned about academic language?
2. How do you define academic language? Probe: How do you define academic language specifically for the discipline of science or mathematics?
3. How do you plan to help students develop academic language in your science or mathematics course?
4. Given these plans to help students develop academic language, how would you modify your instruction specifically for English Language Learners?
5. What is the role of language and literacy in science or mathematics?
6. How might you incorporate language and literacy into your science or mathematics instruction?

Specific Aspects of Science and Mathematics Instruction Part 2

These next few questions are about science and mathematics instruction about practices.

7. In the past month, what have you learned about the eight science and engineering practices (or the eight mathematics practices)?

8. Here are cards with the eight science and engineering practices (or the eight mathematics practices) listed on them.

    a. Please arrange these cards to show how you see them as related to one another.
    b. Which **one** do you think most important to teach students? Why?
    c. Which **one** do you think you need more help to understand? What questions do you have?

Specific Aspects of Science and Mathematics Instruction Part 3

This final set of questions is about engineering.

9. What engineering courses have you taken at either the high school or university level?

10. Please describe what you think engineering is.

    a. Probe: (If yes to #9) What have you learned about engineering from the **engineering** courses you have taken?
    b. Probe: What have you learned about engineering from **education** courses you have taken? (e.g. science methods, CalTeach courses… ex. NGSS or Framework engineering components, Engineering Design, etc.)
    c. Probe: In what ways is "doing" engineering different from "doing" science or mathematics?

11. You drew a concept map that demonstrated what you thought the engineering design process was.

    a. Can you briefly describe your concept map.
    b. Can you elaborate on **one** part of your concept map that you think is the most important. Why?
    c. Which **one** part of your concept map do you think you need more help to understand? Why?
    d. I would like to keep your concept map (make sure name is on it).

14. How might you teach the engineering design process to high school students?

15. Can you describe a specific engineering lesson you might teach to a class of high school students. Probe: What do you think your students would learn about the engineering design process as a result?

Wrap-Up

16. What questions do you have for me?

Thanks!

Figure B5. Initial interview protocol for preservice teachers

[redacted] Teacher Candidate Interview Protocol : December

Thank you for agreeing to be interviewed today. The purpose of this interview is to learn some of the successes and challenges you are experiencing as a teacher candidate. We are trying to redesign the methods courses in science and mathematics to better support beginning teacher learning. We ask that you try to be as candid and as specific as possible.

The information from this interview will not affect your course grades, your teaching placements, or your standing in the [redacted] Teacher Education Program. If there is a question you do not wish to answer, you can ask that it be skipped. If you later wish to revise an answer or to ask that an answer be deleted, you are free to do so as well.

We expect the interview to last about 45 minutes. It is divided into four parts. Do I have your permission to begin recording the interview?

I. Specific Aspects of Science and Mathematics Instruction

These beginning questions are about language and literacy in science or mathematics instruction.

1. In which TEP classes have you learned about academic language?

2. How do you define academic language? Probe: How do you define academic language specifically for the discipline of science or mathematics?

3. How have seen academic language taught in your placements?

4. Task (science or math)

II. Specific Aspects of Science and Mathematics Instruction for ELLS

This next series of questions is about science and mathematics instruction specifically for ELLs.

5. How do you define an ELL student?

6. Have you or are you currently working with ELL students in your placement? If

yes, in what classes?

7. What have you learned about how ELLs learn math or science as a result of your TEP experiences? How have you acted on what you have learned?

8. What have you learned about the effective teaching of ELLs math or science as a result of your TEP experience? How have you acted on what you have learned?

9. What can your ELL students bring as resources to increase the richness in class, such as their own interests, knowledge, language diversity, or cultural background? In what ways have you already drawn on students' funds of knowledge in your placements?

10. What kinds of lessons and activities do you think most effective in teaching ELLs math or science? In what ways have you already implemented such cognitively demanding activities in your placements?

11. What kinds of language opportunities have you provided your ELL math or science students? In what ways have you already implemented such language opportunities in your placements?

12. How do your ELL students differ from one another? How do ELL students compare to those who have been reclassified fluent in English? Probe: Examples include their language proficiency, interests, or ethnicity.

13. What do you think you need to learn to better help ELLs in your classroom? Probe: For example, I need help because I don't know how to support ELLs in writing a lab report.

III. Specific Aspects of Science and Mathematics Instruction

This final set of questions is about engineering.

14. Please describe what you think engineering is.

    a. In what ways is "doing" engineering different from "doing" science or mathematics?
    b. What have you learned about the teaching and learning of engineering since coming into TEP?

15. Can you describe a specific engineering lesson you might teach to a class of high school students. Probe: What do you think your students would learn about the engineering design process as a result?

16. We asked undergraduate interns to draw concept maps of what they thought the engineering design process was. We wanted your opinion on a couple of these concept maps.

    [Show one map. Ask the questions below. Then show the next.]
    a. Do you think this individual has a good understanding of the engineering design process?
    b. Is there anything you think he or she may be missing or misunderstanding?
    c. How does this intern's view of engineering design compare to yours?

<u>IV. Lesson Observation</u>

These final questions are related to the lessons that I will be observing you teach. I have few questions that will help me understand what I am observing.

16. Describe briefly the students that you will be teaching on the day that I observe (age, ability ranges, diversity).

17. What is the purpose of the lesson that you will be teaching?

18. What are your objectives for student learning of content?

19. How will your lesson build understanding of this content?

20. What are the language demands of this lesson?

21. How do you plan to support the learning needs of your students?

<u>Wrap-Up</u>

22. What questions do you have for me?

Thanks!

Figure B6. Winter interview protocol for preservice teachers

[redacted] Teacher Candidate Interview Protocol: Final
June 2016

Thank you for agreeing to be interviewed today. The purpose of this interview is to learn some of the successes and challenges you are experiencing as a teacher candidate. We are trying to redesign the methods courses in science and mathematics to better support beginning teacher learning. We ask that you try to be as candid and as specific as possible.

The information from this interview will not affect your course grades, your teaching placements, or your standing in the [redacted] Teacher Education Program. If there is a question you do not wish to answer, you can ask that it be skipped. If you later wish to revise an answer or to ask that an answer be deleted, you are free to do so as well.

We expect the interview to last about 45 minutes. It is divided into four parts. Do I have your permission to begin recording the interview?

I. Language and Literacy in Science and Mathematics Instruction

These beginning questions are about language and literacy in science or mathematics instruction.

1. What methods course did you take this spring (science with Julie, mathematics with Sarah, ELD with Diana, or the BCLAD course)?
2. What did the instructor of this methods course teach about academic language? Which of these aspects of academic language were new to you?
3. How do expect this course to help you teach academic language as a beginning science or mathematics teacher next year?
4. To dig a little deeper, what did you learn from this methods course about academic language demands? About language rich opportunities for students? About students' funds of knowledge?
5. Given what you have learned in this course, how might you modify the lessons you taught for your edTPA in terms of either or both academic language and ELL instruction?
6. Please look over this Science/Math scenario (see attached page). In light of what you know about academic language and effective ELL instruction, what kinds of modifications, if any, would you make to this activity? Why?

II. Science and Mathematics Practices

These next few questions are about the science and mathematics practices.

7. Over your time in TEP, what have you learned about the eight science and

engineering practices (or the eight mathematics practices)?

8. Here are cards with the eight science and engineering practices (or the eight mathematics practices) listed on them.

   a. Please arrange these cards to show how you see them as related to one another.
   b. Which **one** do you think most important to teach students? Why?
   c. Which **one** do you think you need more help to understand? What questions do you have?

III. Engineering Instruction

This next set of questions is about engineering. (If they didn't draw a concept map about what they think the engineering design process looks like ahead of time, give them 5-10 minutes to do this now)

9. Please describe what you think engineering is.

   a. In what ways is "doing" engineering different from "doing" science or mathematics?

   b. How do you think engineering in the context of education is similar to or different from engineering in the field?

   c. Do you think your understanding of engineering has changed since you began TEP? If yes, how so?

   d. What have you learned about engineering since coming into TEP? How did you learn this? (e.g classes, experiences, other?)

10. Do you consider yourself an engineer? Why or why not?

    a. Do you consider the students or teachers you have worked with throughout TEP engineers? Why or why not?

11. Can you describe a specific engineering lesson you might teach to a class of high school students. Probe: What do you think your students would learn about the engineering design process as a result?

12. The next questions are about your concept map.

    a. Can you describe your concept map in more detail? What do all of the connections you made mean to you?

b. Can you elaborate on one or more parts of your concept map that you think are the most important? Why? Are they important for teaching engineering or for doing engineering?

c. Which part(s) of your concept map do you think you need more help to understand? Why? Is this something you need help understanding for teaching engineering or for doing engineering?

I would like to keep this concept map (make sure you're name is on it).

For [redacted] Teacher Candidates ONLY

13. As part of your [redacted] scholarship, you were placed at [redacted] for the entire school year. What do you see as the strengths of this placement? What do you see as the limitations?

Wrap-Up

14. What questions do you have for me?

Thanks!

Figure B7. Final interview protocol for preservice teachers

Practicing Teachers

[redacted] Mentor Teacher Interview Protocol
(End of 5-Week Summer Experience 2015)

Thank you for agreeing to be interviewed today. The purpose of this interview is to get an experts' opinion about reform-based science and engineering instruction, of what the [redacted] Interns experienced, and of how to improve the program as a whole. We ask that you try to be as candid and as specific as possible.

If there is a question you do not wish to answer, you can ask that it be skipped. If you later wish to revise an answer or to ask that an answer be deleted, you are free to do so as well.

We expect the interview to last about 45 minutes. It is divided into four parts. Do I have your permission to begin recording the interview?

I. Background

I'd like to begin by asking you a few questions about your experiences with the [redacted] Interns'.

1. a. Which classes do you teach that the interns were in?
   b. What was the purpose of these classes?

2. a. Please tell me about the [redacted] interns you have worked with this summer.
   b. What successes did your [redacted] interns experience this year?
   c. What challenges did they encounter?

3. How did you mentor the interns this year? [Probe: Did you meet with them outside of class? Something else?]

4. a. Which of the interns are continuing to participate in your classrooms this fall?
   b. What do you hope they learn about teaching and learning from their continued participation?

5. How might your experiences in [redacted] be enhanced and improved? What suggestions do you have for this program?

II. Engineering Design

This next set of questions is specifically about engineering. The [redacted] Program is interested in preparing excellent science teachers who understand engineering design and can infuse this understanding into their classrooms as they teach.

6. What previous experience do you have with engineering? (e.g., engineering courses have you taken, doing engineering in a formal or informal educational setting, doing engineering professionally, teaching engineering, etc.)

7. a. How would you define engineering?
   b. How do you think engineering in the context of education is similar to or

different from engineering in the field?

8. In what ways is "doing" engineering is different from "doing" science?

9. a. How would you define the engineering design process?
   b. Which part of engineering design do you think is the most important? Why? Is this important for teaching engineering or for doing engineering?
   c. Which part of engineering design do you think you might need more help to understand or want to learn more about? Is this something you want for teaching engineering or for doing engineering?

10. a. What role does the engineering design process play in the courses you teach?
    b. Can you describe a specific engineering lesson that you teach to your high school students where they might learn about the engineering design process?

11. We asked the interns to draw concept maps of what they thought the engineering design process was. We wanted your expert opinion on a couple of these concept maps.

    [Show one map. Ask the questions below. Then show the next.]
    d. Do you think this individual has a good understanding of the engineering design process?
    e. Is there anything you think he or she may be missing or misunderstanding?
    f. How does this intern's view of engineering design compare to yours?

III. High Needs Schools

[redacted] wants to prepare potential teachers for teaching in high needs schools and teaching English Language Learners (ELLs).

12. How do you think the [redacted] interns have been prepared to teach in high needs schools?

13. How do you define academic language? [Probe: How do you define academic language specifically for the discipline of science or engineering?]

14. How do you help students develop academic language in your courses?

15. How do you modify your instruction specifically for English Language Learners?

16. What is the role of language and literacy in science?

IV. Wrap-Up

17. What questions do you have for me?

Thank you so much!

Figure B8. Focus group protocol for practicing teachers

Teacher Educators

[redacted] TEP Faculty Interview Protocol

Thank you for agreeing to be interviewed today. The purpose of this interview is to learn some of the successes and challenges your teacher candidates are experiencing. We are trying to redesign the methods courses in science and mathematics to better support beginning teachers in working with English language learner students. We ask that you try to be as candid and as specific as possible.

If there is a question you do not wish to answer, you can ask that it be skipped. If you later wish to revise an answer or to ask that an answer be deleted, you are free to do so as well.

We expect the interview to last about 45 minutes. It is divided into three parts. Do I have your permission to begin recording the interview?

Specific Aspects of Science and Mathematics Instruction Part 1

These beginning questions are about language and literacy in science or mathematics instruction.

1. *Which classes in TEP do you teach? (individual responses)

2. How do you define academic language for the teacher candidates? Probe: How do you define academic language specifically for the discipline of science or mathematics?

3. How do you teach about academic language in your TEP classes?

4. We will be asking the Teacher Candidates about this Science Scenario (see attached page). What kinds of modifications, if any, would you expect your teacher candidates to make to this activity? Why?

Specific Aspects of Science and Mathematics Instruction for ELLS Part 2

This next series of questions is about science and mathematics instruction specifically for ELLs.

5. How do you define an ELL student?

6. What do you teach teacher candidates about how ELLs learn math or science? Probe: Please provide a specific example.

7. What do you teach teacher candidates about how to effectively teach ELLs math or science? Probe: Please provide a specific example

8. More specifically, what do you teach teacher candidates about the resources ELL students bring to the classroom? In what ways do you hope teacher candidates will draw on students’ funds of knowledge in their placements?

9. What kinds of lessons and activities do you suggest to teacher candidates as most effective in teaching ELLs math or science? In what ways do you hope teacher

candidates will implement cognitively demanding activities in their placements?

10. What kinds of language opportunities do you suggest teacher candidates provide to their ELL math or science students? In what ways do you hope teacher candidates will implement language opportunities in their placements?

11. How do you see ELL students as different from one another? How do ELL students compare to those who have been reclassified fluent in English? Probe: Examples include their language proficiency, interests, or ethnicity.

12. What do you think you need to learn to better help teacher candidates teach ELLs in their classroom?

<u>Engineering Design</u>

This next set of questions is specifically about engineering. The [redacted] Program is interested in preparing excellent science teachers who understand engineering design and can infuse this understanding into their classrooms as they teach.

13. *What previous experience do you have with engineering? (e.g., engineering courses have you taken, doing engineering in a formal or informal educational setting, doing engineering professionally, teaching engineering, etc.) (Individual Responses)

14.
    a. *How would you define engineering? (Individual Responses)
    b. How do you think engineering in the context of education is similar to or different from engineering in the field?

15. In what ways is "doing" engineering is different from "doing" science?

16.
    a. How would you define the engineering design process?
    b. Which part of engineering design do you think is the most important? Why?
    c. Which part of engineering design might you want to learn more about?

17.
    a. What role does the engineering design process play in the courses you teach?
    b. [If not stated above] Can you describe a specific lesson that you teach to teacher candidates where they might learn about the engineering design process?

18. We asked undergraduate interns to draw concept maps of what they thought the engineering design process was. We wanted your expert opinion on a couple of these concept maps.

    [Show one map. Ask the questions below. Then show the next.]

g. Do you think this individual has a good understanding of the engineering design process?
h. Is there anything you think he or she may be missing or misunderstanding?
i. How does this intern's view of engineering design compare to yours?

<u>Wrap-Up</u>

19. What questions do you have for me?

Thanks!

Figure B9. Focus group protocol for teacher educators