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A PHENOMENOGRAPHIC ANALYSIS OF FIRST-YEAR ENGINEERING STUDENTS' EXPERIENCES WITH PROBLEMS INVOLVING MULTIPLE POSSIBLE SOLUTIONS

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ABSTRACT

Dringenberg, Emily, A. Ph. D., Purdue University, August 2015. A Phenomenographic Analysis of First-Year Engineering Students' Experiences with Problems Involving Multiple Possible Solutions. Major Professor: Șenay Purzer.

Engineers are expected to solve problems that are ill-structured. These problems are presented with a lack of necessary information and allow for different ways of engaging with the problem; they are open-ended and involve multiple possible solutions with multiple means of evaluation. In order to allow maximum time for students to develop skills for solving such problems, undergraduate engineering programs can introduce such problems during the first year of students' education, in the form of cornerstone design tasks. This provides students with more opportunities to develop their ability to engage with ill-structured problems, which are characteristic of engineering work. Researchers have documented variation within both the behavior and perceptions of students' early experiences with design problems. General themes include novice-like design behavior, discomfort with lack of information, difficulty with problem scoping, and resistance to ambiguity. To build on these generalizations of students' experiences, a more thorough understanding of the variation in how students experience this phenomenon of engaging with ill-structured problems is needed to design effective learning environments.

This work presents the qualitatively different ways that engineering students experience problems with multiple possible solutions during their first year of engineering studies. Using phenomenography as the methodological framework, data were collected through in-depth, semi-structured interviews with 27 first-year engineering students. The iterative, phenomenographic analysis resulted in seven

descriptive categories for the ways participants experienced problems involving multiple possible solutions. The names of these categories represent the different foci of the students' experiences: completion, transition, iteration, organization, collaboration, reasoning, and growth.

These categories are organized along two crucial dimensions of variation: reaction to ambiguity and role of multiple perspectives. In general, less comprehensive ways of experiencing the phenomenon include seeking information to make the problem more well-structured and thereby allowing the completion of a classroom task. Movement towards more comprehensive ways of experiencing include accepting ambiguity as inherent to the problem, and utilizing multiple perceptions to develop a design solution. The most comprehensive ways of experiencing included experiences that embraced ambiguity as an integral part of the problem solving process and internalized multiple perspectives through working with and learning from others.

The resulting outcome space is of practical use to engineering educators who wish to create more inclusive and effective cornerstone design learning environments. The findings demonstrate that significant variation is present in the way that a small group of first-year engineering students from a single university experience engaging with problems that involve multiple possible solutions. Powerful ways of experiencing this crucial aspect of engineering education include appreciation of the multiple ways of perceiving an ill-structured problem as well as an ability to accept the ambiguity that is associated with engaging with these types of problems. While some students are capable of such an experience, others do seek a single correct answer through an attempt to eliminate ambiguity. Knowing these key axes of variation informs educators' ability to accommodate a range of ways of experiencing design tasks and to design learning environments that foster development in these identified aspects of the experience to promote more meaningful learning experiences.

CHAPTER 1. INTRODUCTION

1.1 Background

Engineers are commonly defined as problem solvers (Bowden & Green, 2005; Mourtos, DeJong-Okamoto, & Rhee, 2004; Pawley, 2009). The problems engineers face are complex and ill-structured, involve unique design contexts and constraints, and require novel applications of mathematics and science (ABET, 2011; Dym, Agogino, Eris, Frey, & Leifer, 2005; Gainsburg, 2006; Jonassen, Strobel, & Lee, 2006; Mann, 1918; National Academy of Engineering, 2005). The grand challenges identified by the National Academy of Engineering, which range from access to clean water to cyber security, present high levels of ambiguity within both the problem definition and problem solution spaces. ABET, the accreditation body of engineering programs, requires that the graduates in engineering must be able to apply principles of mathematics, science and engineering, design and conduct experiments, design systems, components or processes, and solve engineering problems (ABET, 2011). Dym and colleagues (2005) summarize a good engineering designer as someone who: tolerates ambiguity, maintains sight of the bigger picture and handles uncertainty. Within engineering education, Sheppard, Macatangay and Colby (2008) have identified a need for more opportunities to engage design within undergraduate education. Engineering graduates are sometimes unable to apply their theoretical knowledge gained through their time in school to real-world engineering problems (Polson & Jeffries, 2014). These ubiquitous messages related to problem solving within engineering as a field communicate an expectation that engineers contribute to designing solutions to problems that are ill-structured, ambiguous, open-ended and involve multiple possible solutions. In order to prepare engineering students to solve these types of problems, it is important for engineering educators to understand the students' experiences engaging with ill-structured problems, which reflect crucial characteristics of engineering practice.

Specifically, a detailed characterization of the range of experiences that students have when engaging with ill-structured problems will allow the identification of key aspects of how and why these experiences differ. Determining these key aspects will allow educators to design learning environments that emphasize them and promote student's ability to engage with ill-structured problems in meaningful ways. Additionally, developing a characterization of the range of ways that engineering students experience ill-structured problems includes identifying potential thresholds that are crucial in students' development as engineering problem solvers.

Over the last thirty years, problem solving has been a significant area of interest for researchers (Chi, 1981; Hsu, Brewe, Foster, & Harper, 2004; Jonassen, 1997, 2000; Simon, 1978; Smith, 1991). Across many disciplines, research has been conducted to understand how experts approach problems differently than novices (Chi, 1981; Hatano & Inagaki, 1984; Schoenfeld & Herrmann, 1982), problem solving cognition (Mayer, 1992) and the use of representations in problem solving (Brenner et al., 1997; Heller & Reif, 1984; Moore, Miller, Lesh, Stohlmann, & Kim, 2013). These foundational studies focused primarily on the behavior of individuals engaging with problems that are well-structured. However, problem solving research is not limited to characterizing well-structured problem solving experiences. Strategies have also been identified to support students' ability to engage with problems that contain less structure and more ambiguity. When taught explicitly, these strategies improve students' general problem solving abilities (Woods, 2000). However, research is still needed to better understand that way that students experience developing these skills through engaging with ill-structured problems, as their ways of experiencing motivate both their behavior and problem solving approaches.

Research specifically on students' experiences engaging with problems that involve multiple possible solutions has included observing their behavior when learning to engage with design tasks (a type of ill-structured problem solving) and reporting themes across groups of students. For example, Atman and colleagues (2007) found that undergraduate students spend less time problem scoping than experts. In addition, Crismond and Adams (2012) synthesized many problematic behaviors that have been observed in novice designers: attempting to solve the problem prematurely, skipping research, or becoming fixated on one or a few ideas. Similarly, Purzer, Hilpert and Wertz (2011) observed students throughout a semester long design project and documented difficulty with gathering information, defining the problem, and generating solutions. When students do gather information, it is often from convenient sources and superficial (Wertz, Purzer, Fosmire, & Cardella, 2013). Mourtos (2010) specifically observed that a lack of given information and ambiguity in making assumptions to define and represent an ill-structured problem were sources of frustration for engineering students. While these observations offer great insight into the generalized behaviors of novices during design problem solving experiences, they do not capture the perspectives that students have of their learning experiences that motivate these behaviors. Insight into the students' experiences and what they are aware of when engaging with ill-structured problems will provide a better understanding of why students might behave in these ways as well as what key aspects of their awareness contribute to more or less comprehensive ways of experiencing this integral part of engineering education.

Researchers have captured some of the perceptions and outcomes of students learning to engage with ill-structured problems such as design, which tend to vary across studies and contexts (Reid & Solomonides, 2007). Engineering students have both positive and negative reactions to engaging with problems involving multiple possible solutions (Atman, Chimka, Bursic, & Nachtmann, 1999). A case study of electrical engineering students revealed that students struggle with the introduction of ill-defined problems and perceive themselves to have learned less than in more traditional lecture settings (Yadav, Subedi, Lundeberg, & Bunting, 2011). In contrast, Woods and colleagues (1997) report significant increases in students' confidence after experiences engaging with ill-structured problems.

So, while previous work informs our understanding of typical behavior of novice designers and the presence of variation in their perceptions of engaging with ill-structured problems, a more comprehensive characterization of variation in such experiences is needed to avoid generalizing all students as limited in awareness or bound to behave in a particular way. The results of this study contribute to problem solving literature by identifying ways to facilitate more comprehensive ways of experiencing problems involving multiple possible solutions within undergraduate engineering education.

1.2 Motivation

Descriptions of novice design behavior do not provide a nuanced level of detail into the variation within the experiences of novices. Rather, broad generalizations are made about this group of learners that leave a gap in the literature for research focused on the qualitatively different ways that engineering students experience problems involving multiple possible solutions. This study aims to contribute to this gap literature by characterizing the variation in experiences of engineering students engaging with ill-structured problems in the form of design tasks. A more detailed characterization of the range of experiences that first-year engineering students have with ill-structured problems will inform our ability to accommodate their learning needs. Also, this study aims to challenge a generalization that all first-year students understand their problem solving ways in a simplistic manner. Because early experiences with ill-structured problems are key to students' development as engineering students, close attention to this aspect of the engineering education program is warranted.

1.3 Research Question

The following research question motivates the study:
What are the qualitatively different ways that first-year engineering students experience problems with multiple possible solutions?

1.4 Implications

Understanding the experiences of students as they learn to engage with design tasks is crucial to improving engineering education. Because the outcomes of an educational phenomenon are interlinked with the learner's experience of that phenomenon (Marton & Booth, 1997), a deeper understanding of students' experiences is necessary for educators to develop learning environments which are more inclusive and effective. A better understanding how diverse groups of engineering students experience this important type of problem solving will provide insight into how to create learning experiences that accommodate a wide range of learners and promote development in key aspects identified to lead to more comprehensive learning experiences.

This study provides detailed descriptions of the range of different experiences that students have while engaging with ill-structured problems early in their engineering training. By identifying the key aspects that influence the variation across experiences, this work will inform educators' abilities to draw students' attention explicitly to those key aspects. The range of experiences is organized into a logical structure that identifies key themes of expanding awareness along with potential thresholds for experiencing ill-structured problems in meaningful ways. This contribution may help engineering educators to produce better learning outcomes and engineering graduates that are more prepared to tackle engineering problems in the workplace. In addition, students can be made aware of the range of possible experiences to prompt reflection on their own meaning-making when engaging with ill-structured problems.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

In this literature review, I present research that serves as a framework for understanding what qualifies problems as ill-structured for the purpose of this study, including the following characteristics: lacking all relevant information, containing ambiguity in the problem solving process, and possessing multiple possible solutions that require judgment for evaluation. In addition to the ways that these characteristics describe the nature of ill-structured problems, I also include research describing the skills that students need to engage with problems possessing these characteristics. Additionally, I include literature that speaks to the way students experience problems involving multiple possible solutions such as the broad culture of engineering science, and traits of capstone and cornerstone design courses. Finally, literature portraying the variation in student experiences with ill-structured problems as well as some broad themes across experiences is included.

2.2 Theoretical Framework

The phenomenon that this dissertation investigates is students engaging with problems that are ill-structured and reflect engineering problem solving, such as design work. The theoretical framework that specifically informs the types of problems chosen represent this phenomenon comes from an adaptation of Jonassen's classification of problems. The use of this particular framework helps to situate the phenomenon of interest within the wide range of problem solving literature. Due to Jonassen's prominence in problem solving literature as well as the explicit connections to engineering problem solving in his framework (Jonassen et al., 2006), this study uses his key idea of structuredness to identify problems of interest. This section describes the key elements of Jonassen's work in combination with additional literature, which I used to develop my framework for classifying problems. A description of these problems also helps to clarify to which sorts of problems the findings of this study may be transferrable.

2.2.1 Ill-Structured Problems

Problems have many characteristics that distinguish them from one another. Throughout the introduction, I used many terms interchangeably to describe the type of problems that are of interest in this study, such as complex, ill-structured, novel, ambiguous, open-ended, ill-defined, and multiple solution. This reflects the variety of ways that problems are described and characterized throughout literature. To provide clarity, my framework focuses on a notable characteristic used to classify problems, structuredness, which Jonassen (2000) uses to divide problems into ill-structured or well-structured.

Jonassen (1997, p. 67) suggests that different types of problems can be considered as a "continuum from decontextualized problems with convergent solutions to very contextualized problems with multiple solutions." The former are referred to as well-structured, the latter, ill-structured. This way of classifying problems serves as a basis for the theoretical framework of this study. In later work, Jonassen (2000) provides a more detailed schema for problem classification based on a synthesis of problems that differ with regard to structuredness (again), abstractness and complexity for a large number of problems ranging from logical problems (e.g. solving a Rubik's Cube) to dilemmas (e.g. issues surrounding gun control). While considering the two ends of the spectrum helps to categorize problems, a dichotomy is over simplified. However, this framework helps to characterize ill-structured problems, such as design tasks, that are characteristic of engineering work (Jonassen et al., 2006; Sheppard et al., 2008).

As shown in Table 1, ill-structured problems can be identified based on four major aspects. Throughout this study, when I refer to problems as "ill-structured," I am describing a phenomenon where a learner is engaging with problem that has all of the characteristics summarized in this table.

Table 2.1. Key Aspects of Ill-Structured Problems

Aspect of Problem	Description	Example
Information Given	Necessary information is missing or may not be known with any degree of confidence	A user need is presented to a design team without a formal definition of the problem or potentially relevant data. Constraints are presented without specific numerical values.
Process Ambiguity	Uncertainty exists about which concepts, rules, and principles are necessary for the solution or how they are organized	The design team must make assumptions about how to navigate the design process. No information is provided on where or how to start and when or how to stop.
Number of Possible Solutions	The problem may possess multiple solutions, solution paths, or no solutions at all	There are many ways the design team might potentially address a user need.
Means of Evaluating	Multiple criteria exist for evaluating solutions requiring learners to make judgments about the problem and defend them	The design team must provide justification and rationale for their design decisions as well as their final solution.

While Jonassen provides a synthesis that includes these four aspects presented in Table 2.1, extant literature further supports and expands upon these four aspects of ill-structured problems.

The following four sections provide additional information regarding the nature of ill-structured problems that were considered when identifying the phenomenon of interest for this study. Extant research about the behavior of students engaging with ill-structured problems is also presented to demonstrate some of what we do know about how students engage with ill-structured problems. Section 2.3 includes information regarding the ways students experience this type of problem solving, which I use to identify the gap in literature this study contributes to. In general, much of the research presented here provides generalizations across students, so this work builds on these generalizations by characterizing variation in experience.

2.2.1.1 Information Given

The first major characteristic of ill-structured problems is a lack of information provided. In addition to Jonassen, Simon (1978), identified missing information as a distinguishing aspect of the type of problem solving experience being investigated in this study; what information counts as relevant is often not clear. Similarly, King and Kitchener (2004) distinguish ill-structured problems as problems that cannot be completely defined. Adams, Turns & Atman (2003) identified "problem setting" as a important feature of being an effective designer. The lack of information provided in ill-structured problems is in contrast to engineering students' interactions with typical textbook mathematics or physics problems, which are described as, "well defined, the 'givens' of the problem were presented in the problem statement, and the constraints of the problem were provided in the problem statement or were known to the solver" (Voss, 1988, p. 75). The amount of information provided is critical when training engineering students to solve real-world engineering problems because "we lack information; there are errors in the information we do have; we never have enough resources" (Woods et al., 1997, p. 76). Furthermore, a study of how practicing engineers conceptualize the design process revealed an emphasis on problem scoping, which is a dominant characteristic of problems with multiple possible solutions (Mosborg et al., 2005).

Because ill-structured problems have a lack of information as a distinguishing characteristic, particular behaviors are needed to respond effectively. Prior research has identified necessary behaviors for engaging with ill-structured problems to include problem definition and information gathering. For example, learners are required to engage in problem structuring before they are able to start developing solutions (Goel & Pirolli, 1992). This portion of the problem solving process may even involve determining if the problem actually exists (Jonassen, 1997). This process of exploring the complex problem has also been referred to as problem framing, which requires the learner to develop a complex way of perceiving a particular design problem (Dorst, 2011). A design strategy for developing this skill includes delaying design decisions in order to better understand, or frame, the problem (Crismond & Adams, 2012).

Designers must gather information based on user-specified needs, and they also rely on their own preferences and abilities (Dorst, 2003). While informed by initial conditions, such as user constraints, the definition of a design problem will change as the designer engages with it. Also, we frame problems in different ways based on our backgrounds and past histories, interests, etc. (Schön, 1987). Kolko (2010) also describes this requirement for engaging with design tasks with an emphasis on re-framing a problem in a way that extends beyond one's own personal experience and culture. Some designers have been observed to define a problem only based on their initial solution concepts, rather than spending time rigorously defining the problem itself (Cross, 2001).

Atman et al. (1999) observed first-year students spending less time on problem scoping than more senior students, and additional research findings have observed the same trend (Allam, Whitfield, & Phanthanousy, 2012; Swenson, Portsmore, & Danahy, 2014). However, later work (Atman, Cardella, Turns, & Adams, 2005) documented first-year students spending most of their time on problem scoping, which provides evidence of variation between existing studies. All undergraduate students have been observed to spend less time on problem scoping than expert designers (Atman et al., 2007). Students have also been observed exhibiting behavior that suggests they expect to be told clearly what to do to solve the problem (Hjalmarson, Cardella, & Adams, 2007). When students experience problems that do not contain all relevant information, a signification portion of them identify this as the most difficult part of the process of engaging with an ill-structured problem (Mourtos, 2010).

2.2.1.2 Process Ambiguity

Ill-structured problems do not have a set or single correct way of proceeding through an established problem solving process. Ambiguity within the design process has been referred to as the co-evolution of the problem and solution space, with the goal of the designer being to find a "matching problem-solution pair" (Dorst, 2003). This is in contrast to well-structured problem where an established method leads to a single correct answer. Cross (1999) identifies the emergent nature of the process as a key characteristic of design problems, where the solution and problem develop simultaneously. Design processes do not have simple "legal move generators," or a fixed amount of available actions, to find alternatives at each step along the way (Simon, 1978).

Behaviors that are necessary to navigate this aspect of ill-structured problems include decision making, using abductive reasoning, and reflecting. Throughout the ambiguous process of engaging with design tasks, learners must decide how to build their knowledge, generate, represent, and evaluate ideas as well as conduct experiments and troubleshoot as needed (Crismond & Adams, 2012). Marston and Mistree argue that, "the principal role of the designer is to make decisions. Decisions help to bridge the gaps between idea and reality, decisions serve as markers to identify the progression of the design from initiation to implementation and termination" (as cited in (Jonassen, 2012, p. 342)).

A particular type of reasoning, abductive reasoning, has been used to describe the way that designers deal with the uncertainty in finding a matching problem and solution pair (Dorst, 2011). This process is unique from the common practices of employing inductive reasoning (e.g. scientific discovery) or deductive reasoning (e.g. theoretical justification) as it requires adopting a frame for design and then using it along with the corresponding working principle to generate the desired value (Dorst, 2011). Abduction "allows for the creation of new knowledge and insight—C is introduced as a best guess for why B is occurring, yet C is not part of the original set of premises" (Kolko, 2010, p. 20).

When reacting to the ambiguity within the problem solving process, designers may behave opportunistically and may frequently switch the types of cognitive activity they engage in (Cross, 2001). When navigating process ambiguity, a common difficulty for students is to be hung up on a single "right" way of developing a solution (Diefes-Dux, Moore, Zawojewski, Imbrie, & Follman, 2004). Mourtos (2010) observed that students also had difficulty determining which assumptions were appropriate to simplify the problem. Despite these observations, the quality of a design has been linked to the degree with which engineering students follow a logical design process, or sequence of processes (Radcliffe & Lee, 1989).

In order to develop these reasoning skills that are unique to design problems and the uncertainty in the process of solving ill-structured problems, learners should be prompted to reflect on their process and the strategies they are using throughout their engagement with the design task (Crismond & Adams, 2012). Schön (1987) presents reflection, specifically “reflection-in-action,” as a necessary component of learning to design in any context. Schön’s framework for reflection as a critical part of design has been used to provide empirical evidence that “engaging in reflective conversation across problem setting and problem solving activities are important features of effective design practice” (Adams et al., 2003, p. 292).

2.2.1.3 Number of Possible Solutions

Possessing multiple possible solutions, or open-endedness, has been identified as another primary distinction for problem classification (Douglas, Koro-Ljungberg, McNeill, Malcolm, & Therriault, 2012; Dym, 1994). While engineers may work within a convergent knowledge domain, design problems “often operate under a diametrically opposite premise: for any given question, there exist multiple alternative known answers” (Dym et al., 2005, p. 105). The efforts of Mourtos and colleagues (2004) to generate engineering tasks that develop ill-structured problem solving behavior beyond exercise solving resulted in open-ended problems, which have multiple possible solutions. The generation of multiple possible solution spaces is derived from multiple opinions or perspectives (Jonassen, 1997).

The possibility of multiple possible solutions requires designers to generate solutions and go beyond their initial ideas to consider alternative concepts rather than becoming fixated on or attached to a particular concept (Cross, 2001). Multiple solutions may result as each designer situates the problem based on their own perspective (Dorst, 2003). Productive design behavior includes working with multiple ideas through brainstorming and divergent thinking (Crismond & Adams, 2012). The evaluation needed to reach a consensus on this shared vision is described in more detail in the next section.

Research on the ways in which undergraduate engineering students have behaved when confronted with an open-ended problem revealed three different reactions: becoming overwhelmed by complexity, exhibiting uncertainty and self-doubt, and utilizing a systematic and linear design process (Douglas et al., 2012). Students who were able to establish and use a systematic process outperformed those who were overwhelmed or uncertain due to the ambiguity of the problem. Students have been found to respond to uncertainty within problem solving in a variety of additional ways including the following: expressing frustration, devising strategies to collect information, estimating, and decomposing the problem into smaller parts (Hjalmarson et al., 2007).

2.2.1.4 Means of Evaluating Solutions

The final key aspect of the nature of problems that are considered to represent the phenomenon of ill-structured problem solving for this study is the means of evaluating a potential solution to a problem. King and Kitchener (2004) describe ill-structured problems as unable to be solved with certainty. Simon (1978) notes that there is less clear criteria for when the goal of the design task as been attained. It is also possible that because these types of complex problems have multiple possible solutions that there may not be a consensus among experts in the field upon any particular solution (Voss, 1988).

Since engineering problems have multiple valid ways of evaluating solutions, engaging with this type of problem solving requires decision making. In his discussion of decision making within the engineering design process, Jonassen identifies the potential of these decisions to be “complex, involving multiple options, multiple criteria, along with numerous perspectives on each criteria” (2012, p. 342). Problem solvers are allowed flexibility in the way the evaluate their solutions and justify their decision making throughout the problem solving process, which includes the need to use personalized stopping rules based on their own experience as there is no single right or wrong answer to indicate the design process is complete (Goel & Pirolli, 1992).

A common way of articulating and using criteria ranking to converge to a final solution within engineering is the use of decision matrices (Jonassen, 2012). Learners are also required to use judgment to evaluate the multiple possible solutions they have generated. This process includes considering multiple perspectives and using justification to create argument for degrees of rightness where a single, correct solution doesn't exist. Teaching ill-structured problem solving can also require addressing student attitudes and values (Mourtos, 2010).

Hence, to be considered representative of the phenomenon of engineering problems for this study, problems must be presented without all relevant information, contain ambiguity within the process, posses multiple possible solutions and require judgment for evaluation of possible solutions. The recruitment of participants from courses including such experiences is detailed in Chapter 3.

2.2.2 Need to Study Ill-Structured Problems

The four previous sections outline key features of ill-structured problems as well as the behaviors necessary for engaging with such problems. Some work, especially in the development of artificial intelligence, was conducted with the assumption that computer programs could be developed to solve ill-structured problems in a way that resembled the way humans do (Reitman, 1965). However, this view has since been challenged due to a lack of evidence that well- and ill-structured problems are the same (Dorst, 2006). For example, Shin, Jonassen and McGee (2003) found that while domain-specific and justifications skills were significant predictors of students' abilities to solve well-structured problems, success with ill-structured problems in a new context had additional significant predictors including attitudes towards science and metacognitive awareness. Additional research has documented the differences in skills required to engage successfully with ill-structured problems, one major influence has been epistemic beliefs being of significant importance (Schraw, Dunkle, & Bendixen, 1995). Strategies for problem solving can be considered to be separate from content knowledge and can be taught explicitly (Mourtos, 2010; Woods & Crowe, 1984).

Engineering students must develop skills and strategies for engaging with ill-structured problems that are different than those for engaging with well-structured problems. While these strategies are known and observations of student behavior provides basis for generalizing students' reactions, further research on the experiences of students as they experiences the phenomenon of ill-structured problem solving is warranted. The next section reviews literature that focuses more on the experiences of students to identify the contribution of this study.

2.3 Ways Students Experience Ill-Structured Problems

Within engineering education, there are many different factors that contribute to the ways in which engineering students experience ill-structured problems. Over time, the ways in which engineering students have been expected to engage with different types of problems has changed. In general, engineering education in the United States has undergone a transition from technical training for military purposes to the current focus on engineering science accompanied by communication skills to solve novel problems. This section provides some literature related to how students experience ill-structured problem solving within the current model of engineering education in the United States.

2.3.1 Engineering Science Model

Although engineering education has emphasized technical training in the past, the current model for engineering education is largely oriented towards engineering built on theoretical math and science. Engineers are called to solve ill-structured problems, yet they experience most of their training in the current undergraduate education system as focused on solving well-structured problems with a single right answer, which does not prepare them adequately (Sheppard et al., 2008). Well-structured problems are the most common type of problems that students in schools are asked to engage with (Jonassen, 1997). These problems compose exams and homework, and they are ultimately mathematical and require being solved symbolically (Bucciarelli, 1994). In addition, these problems may be considered as abstract and highly simplified, which do not do an adequate job of connecting students with engineering work (Agogino, Sheppard, & Oladipupo, 1992). A focus on engineering science and analysis alone results in students that are not prepared to practice in industry (Dym et al., 2005).

The curricular focus on solving well-structured problems develops students' belief that design is less important than engineering science, a belief that they do not hold when entering engineering programs (Downey & Lucena, 2003). This has a critical impact on students, who are not only learning knowledge and skills, but also developing their understanding of what it means to be an engineer (Dall'Alba, 2009). Relatedly, Downey and Lucena (2003, p. 170) have observed and reported that,

> "*During the undergraduate years, engineering students solve thousands of problems either on paper or in programs, each time drawing sharp boundaries around the problem, abstracting out its mathematical content, then applying the numbers back to the original problem as its solution. They know to keep any feelings they have about the problem out of the process; these are irrelevant and can only get in the way*."

Recently students have been found to use engineering textbooks to find analogous problems which can serve as examples and provide key equations when solving problems, and this behavior allows students to solve problems without considering real-world constraints that are critical in industry (Lee, McNeill, Douglas, Koro-Ljungberg, & Therriault, 2013). If engineering programs provide primarily experiences with well-structured problem solving, students may lack necessary experiencing learning to develop the distinct skills required for engaging with ill-structured problems.

2.3.2 Capstone and Cornerstone Design

Along with the current emphasis on engineering as science and well-structured problem solving, undergraduate engineering programs are required to address the need for students to experience design, which most commonly occurs in the form of design opportunities. Sheppard et al. (2008) explains that the relatively recent addition of design as a component of engineering education focuses primarily on teaching students to define the problem, generate multiple feasible solutions, and then progress towards an optimal solution. Often, this experience comes in the form of capstone design, which exposes students to ill-structured problem solving towards the end of an undergraduate student's training. Design experience could also include cornerstone, which occurs starting in the first semester of the undergraduate experience. Both of these approaches as ways undergraduate engineering students experience ill-structured problems are detailed next.

2.3.2.1 Capstone Design

Traditionally, engineering programs have addressed the need for solving problems with multiple possible solutions by including capstone design projects towards the end of a hierarchically structured program. This sequential curricular structure assumes that students need time to develop technical skills and engineering science knowledge before transitioning to more complex problem solving as upper-level students. A review of undergraduate engineering student curricula revealed that opportunities for working on design problems were most frequently offered to students in the latter half of their studies; their autonomy increased with time (Sheppard et al., 2008; Stevens, O'Connor, Garrison, Jocuns, & Amos, 2008). If students experience ill-structured problem solving through capstone design, they may experience design as a downstream activity. Students are also assumed to be able to deliberately transfer their content knowledge towards solving a novel engineering problem. In general, capstone design is an experience where students are expected to develop their skills in a linear fashion, graduating to ill-structured problem solving towards the end of their education.

As the most popular method of incorporating design into engineering curriculum, capstone courses are well documented. A summary of information on capstone education revealed that the way that students participate in these design courses vary based on department in their length and focus; they may include either simulations of real world projects or true industry partnerships (Dutson, Todd, Magleby, & Sorensen, 1997). Evaluation takes on a new form, where faculty are required to provide subjective measures, which often reflect individuals' efforts related to communication and teamwork (Dutson et al., 1997; Sheppard et al., 2008).

While this capstone approach to introducing ill-structured problems is most common in engineering schools, it does not provide students with many opportunities to practice engaging with such problems throughout their college experience. When held to the end of the undergraduate experience, capstone design may serve as a needed introduction to real world problem solving, but it is also in stark contrast to their previous experiences problem solving in a deductive fashion in their engineering science courses (Sheppard et al., 2008). A different, and arguably better, approach comes in the form of cornerstone design.

2.3.2.2 Cornerstone Design

A popular curricular change to provide students with a taste of real engineering work early in their schooling is to move design experiences to the students' first year; rather than "capstone design," students can experience "cornerstone design," as it was dubbed in the 1990s (Dym, 1999). This change in curricular structure removes the more traditional pattern of waiting to expose students to ill-structured problem solving until they have completed many engineering science prerequisites. First year students, despite their limited technical background, can do meaningful design work when given the opportunity to engage with well-designed design tasks (Dym, 1994). Many aspects of the course may be similar to a capstone design course, except there is less focus on discipline-specific artifacts and more focus on conceptual design methods (Dym et al., 2005). This can also include focusing on overall integration of the curriculum (Bordogna, Fromm, & Ernst, 1993).

When students experience ill-structured problem solving as cornerstone design, they are provided with both the experiential nature of design problems as well as an understanding of design as a cognitive activity through design techniques (Dym, 1994). Additional benefits of cornerstone design experiences include, "enhance student interest in engineering, enhance student retention in engineering programs, motivate learning in upper division engineering science courses, and enhance performance in capstone design courses and experiences" (Dym et al., 2005, p. 110). Typically, studies in this area report both data that quantifies these benefits (e.g. retention rates) as well as anecdotal evidence of student satisfaction through focus groups or surveys (Olds & Miller, 2004; Pavelich & Moore, 1996). Allowing students to engage with design tasks has been shown to promote retention, especially of women and underrepresented minorities (Agogino et al., 1992). Design experiences have also been shown to significantly increase the self-efficacy of first-year students (Booth & Doyle, 2012).

One example of employing cornerstone design comes from the Colorado School of Mines, which reports that their "hands-on approach introduces our science and engineering students at the beginning of their college careers to the kinds of problem-solving abilities they will need as professionals" (Pavelich, Olds, & Miller, 1995, p. 45). Many other undergraduate engineering programs employ design projects in their first-year programs, including Stevens Institute of Technology (Cole, Gallois, & Sheppard, 1999), Tufts University (Swenson et al., 2014), The Ohio State University (Allam et al., 2012), University of Virginia (Richards & Carlson-Skalak, 1997), and Texas A & M University (Bodnar et al., 2012) among others. Such efforts are supported by research that has shown that students can improve their design abilities just a single semester into their college experience (Atman et al., 1999).

In summary, students can be required to engage with ill-structured problem solving early and throughout their college experience (cornerstone design) or towards the end of their education (capstone design). Literature provides support for the cornerstone design approach, so this work will explore the experience of students engaging with ill-structured problems during their first year as engineering students. It is necessary to understand the experience of our students in order to design a more effective, user-centered learning environment. Beyond understanding the external factors affecting how students experience ill-structured problem solving, it is of particular interest to understand their perceptions of this important experience in their development as engineers. The following section reviews work that has already been done to characterize students' perceptions of their early experiences with ill-structured problems.

2.4 Students' Perceptions of Ill-Structured Problem Solving

Students display significant amounts of variation in the ways that they experience, or navigate, their time within the engineering education system (Stevens et al., 2008). This variation includes their perceptions of what they have learned and their emotional reactions to the experience. In addition to variation, there are some broad themes that have been identified that frame the experience of students engaging with ill-structured problems.

2.4.1 Variations in Perceptions of Classroom Experience

Woods (1994) likened students' early experiences with ill-structured problem solving (here, in the form of problem based learning) to experiencing trauma—students initially experienced shock, progressed through resistance, and finally, with time, moved into acceptance. Similarly, students being introduced to a learner-centered classroom resist that change in their classroom experience (Doyle, 2008). Students have been found to express emotional distress when describing the experience. The introduction to more open-ended problems can cause students to be "nervous because they were no longer looking for 'one right answer'" (Stevens et al., 2008, p. 359). Additionally,

> *"the shift to more open-ended problem solving…[was a source] of frustration for some [engineering students], seeming both an abrupt and a radical departure from prior understandings of problem solving. For example, when asked about his capstone design project, [a senior in engineering] said that he was 'intimidated' by the 'really open-ended stuff'"* (Stevens et al., 2008, p. 359).

In a similar way, (Atman et al., 1999, p. 148) captured a students' experience as "deep, mind boggling, long, and huge". In later work, Atman and colleagues (2010, p. 37) found students demonstrated repeated emotional distress to being introduced to ill-structured problems, "so it's scary…I might be nearing the end of black and white, right and wrong phase."

Students may also perceive to have learned less when engaging with open-ended problem solving, despite a documented increase in learning gains (Yadav et al., 2011). Downey and Lucena (2003) conducted an ethnographic study of engineering students engaging with design, and found more resistant and negative themes, including:

- initial confusion with problem definition
- perceiving the instructor as absolute
- fitting design into the engineering sciences
- resisting iteration and design outside of their perceived discipline

Students early in their college career who are asked to engage with ill-structured problems show frustration for the first or second project, but these feelings are resolved and students show improvement with practice (Pavelich et al., 1995).

In contrast to resistance and emotional distress, first-year engineering students have also been found capable of and interested in starting to engage with this type of problem solving early. While senior students were more confident when describing their approach to an ill-structured problem, first-year students showed evidence of improving their design abilities after only a semester in engineering (Atman et al., 1999). Some first-year students enjoy this type of learning:

> *"I like this type of problem. I wish I had more of them because for instance in a math class you're just crunching numbers…I like these types of problems, 'cause it's more like real life, instead of dividing everything into certain subjects, you know. I would like to do more of these in the future"* (Atman et al., 1999, p. 152).

When polling students who had engaged with open-ended problems in courses in junior-level engineering courses, Mourtos (2010) received primarily positive responses from students including a perspective that the class was interesting, explained clearly and meaningful to learning. Courter, Millar and Lyons (1998) captured the following broad themes of students' engaging with ill-structured problems, which are positive:

- students framed their experience with working on teams
- students experience a real-world, hands-on, customer based project
- students gained a motivating context for engineering

- students increased their self-esteem and confidence
- students perceived faculty as more approachable
- students build peer friendships through the common experience

Despite their worry throughout the process, students did acknowledge engaging with ambiguity did increase their understanding of the material (Mourtos, 2010).

In summary, students experience design in a variety of ways ranging from positive to negative, and many of those findings have been generalized themes across experiences. A better understanding of the various ways that first-year engineering students experience ill-structured problem solving is important to the on-going improvement of engineering education at large. Atman, et al. (2010) claim that the experience of students is a fundamental research area to inform the ongoing evolution of engineering education. Therefore, this work aims to capture the variation of first-year engineering students' experiences with problems with multiple possible solutions.

2.5 Potential Thresholds for Ill-structured Problem Solving

While not used as a formal framework, the idea of thresholds for experiencing ill-structured problem solving informed this investigation. Previous phenomenological studies have developed outcome spaces that included the identification of thresholds for meaningful experiences (Hsu, 2015; Zoltowski, Oakes, & Cardella, 2012). As noted above, students engaging with ill-structured problems may have negative or positive learning experiences. My analysis was guided, in part, by the aim to characterize a potential threshold for students to have positive or meaningful learning experiences.

An example of a previously identified threshold for ill-structured problem solving is students' personal epistemology. Epistemological levels have been specifically linked to engineering problem solving. Students with higher levels of epistemological development have been observed to discuss the importance of ill-structured problems, and students with lower levels of epistemological development comment frequently on their struggle with the transition to engaging with such problems (Marra & Palmer, 2004). Epistemological beliefs have also been identified specifically as a barrier to learning to solve ill-structured problems (Garland, 1993). Marra, Palmer and Litzinger's (2000) look at first year students in an engineering design course suggested that in order to engage with open-ended design projects, students must have an epistemological perspective that is mature enough to allow them to see that multiple solutions are possible and that they must develop criteria to evaluate those solutions

Some researchers have even assigned a specific level of epistemological development as the threshold to being able to engage competently with ill-structured problems. For example, Pavelich, et al. (1995) in their work with engineering students argue that the goal of engineering education should place graduates at a level six on Perry's scale for epistemological development. This is where students can use evidence, evaluate alternatives and make judgments based on context work solving problems. A student who has not advanced to this level may begin to use evidence, but may still hold the perspective that the activity is "'how authority wants us to think' rather than as a consequence of the nature of knowledge" (Pavelich et al., 1995, p. 50).

This research on personal epistemology is a demonstration that particular thresholds may be identified for students to have meaningful learning experiences with ill-structured problem solving, which can inform the design of effective learning environments. While personal epistemology was not used explicitly as a framework, the goal of identifying additional potential thresholds did inform both my study design and analysis.

2.6 Contribution of this Study to a Gap in Literature

The reviewed literature provides evidence that problems exist in different forms ranging from well-structured problems with a single possible solution to ill-structured problems with multiple possible solutions. These forms require different skills and behaviors of the learners; developing skills for well-structured problems may not transfer to engaging effectively with ill-structure problems. Engineers are ultimately required to engage with problems that have multiple possible solutions, and cornerstone design is an important aspect of engineering students' development towards that aim. Students experience early design problems in a variety of ways, and some common themes across experiences have been documented. This study will expand upon these themes by developing a more detailed outcome space to characterize the key variation across a range of students' experiences.

CHAPTER 3. METHODOLOGY

3.1 Introduction

With my posed research question, I aim to understand the qualitatively different ways that first-year engineering students experience engaging with problems with multiple possible solutions. Phenomenography, which allows researchers to capture variation across experiences with a given phenomenon, has been selected as the most appropriate methodological framework for answering this question of interest. This section provides an overview of phenomenography as a research approach as well as a description of the phenomena of interest, participants, and context for the study. A description of the research design is also provided, including data collection and data analysis procedures. The methodological framework of phenomenography guided methodological decisions throughout the research design and implementation process.

3.2 Phenomenography

In the past 40 years, phenomenography has been used to study a range of phenomenon related to learning and has been employed by researchers with differences in research purpose, data collection, and analysis. Within engineering education, phenomenography has been identified as an emergent research framework (Case & Light, 2011). As such, it has previously been selected as appropriate to study qualitatively different student experiences within an engineering context. For example, Hutchison-Green, Follman, and Bodner (2008) used a phenomenographic approach to explore how first semester engineering students formed their engineering efficacy beliefs. Phenomenography has also been used to gain insight into the experience of students in the context of experiencing human-centered design (Zoltowski et al., 2012), transition into first-year engineering (Salzman, 2014), engineering in the workplace (Pan, 2014), and interdisciplinary engineering experiences (Hsu, 2015). These studies provide examples of how this methodological approach has been successful in understanding experiences within engineering education.

Emerging from researchers in Sweden in the 1970s (Marton, 1981), phenomenography developed out of a need for a pragmatic way to describe the limited qualitatively different ways that individuals experienced a given phenomenon (Marton, 1988). The roots of phenomenography revolve around the question, “Why do some people learn better than others?” (Marton & Booth, 1997, p. 15). The overall purpose of this methodology is to develop categorical descriptions of these different ways that people experience (understand, conceptualize, apprehend, etc.) a particular phenomenon of interest and the logical way these categories are related (Marton & Booth, 1997). This is done by assuming a non-dualistic ontology; the reality being investigated is the one constituted by the relationship between the phenomenon of interest and the participants (Marton, 1988). Marton (1988, p. 181) describes the research approach, “we are not trying to describe things ‘as they are’…we are trying to characterize how they appear to people.”

Variation across approaches to phenomenographic research are commonly categorized as Marton and colleagues from Sweden in contrast to Bowden or Åkerlind from Australia. While there is certainly no distinct line between any of the methodological nuances of phenomenographic studies (they are all built on similar ontological and philosophical assumptions), some of the more prominent differences include methods of recruitment, data collection, data analysis and motivation for using the resulting outcome space. For example, the Australian approach to phenomenography may sample participants from a range of contexts in order to capture variation across as broad phenomenon. In contrast, the Swedish approach most recently focuses on engaging all participants in the exact same experience, such as a think-aloud activity, in order to capture variation within that particular experience and context (Marton, 2014). Recent work reviewing the differences between approaches highlights variation in handling interview transcripts, conducting analysis individually or collaboratively, and the preferred procedure for developing categories in relation to developing the structure between the categories (Åkerlind, 2012).

This study utilizes primarily methodological decisions that align with the Australian practices. Bowden (2005) distinguishes his work as motivated to create a practical outcome space that not only characterizes different experiences, but is useful to practitioners when designing learning environments to be more comprehensive, which is aligned with my overall aim of conducting research to improve engineering education. However, I made decisions that were justifiable within my study rather than in an effort to adhere to any existing view of phenomenography.

The most typical method of data collection for phenomenography is in-depth interviews, where the transcription of these interviews is the primary data source (Marton, 1988). The interviews are conducted in a conversational way, starting with an opening prompt and then following the participant in a discussion while tying the salient points of their description of an experience back to the phenomenon of interest. Rather than always asking pre-set questions in a particular order, the interviews consist of strategic follow up questions, which focus on why participants behaved in a certain way or felt their behavior was important when experiencing the phenomenon (Åkerlind, 2005b). These transcripts are then analyzed in an exploratory, iterative process consisting of sorting transcripts into categories, describing variation within and between categories, and using empirical evidence to guide this process.

The results of a phenomenographic study are categories that describe the various ways in which participants experience the phenomena of interest. The categories are developed through iterative exploration of the data; no a-priori codes are used. In addition to categories that describe the qualitatively different ways of experiencing the phenomenon of interest, the outcome space also includes some sort of logical relationship between the categories. With the aim of informing instructional practice, the analysis should seek evidence that some categories of experience are more comprehensive than others (Bowden & Green, 2005) .

In terms of educational implications, the qualitatively different learning outcomes are linked to qualitatively different learning experiences (Bowden, 2000). A better understanding of the different experiences of students learning to engage with problems with multiple possible solutions will inform engineering educators' attempts to make the experience more meaningful, inclusive, and effective, which may lead to an increase in desired learning outcomes. Having provided a brief overview of this methodological approach, the detailed method I used to answer my research question is described next.

3.3 Research Method

This section provides a description of the detailed methods that I used to conduct my study based on the research approach of phenomenography, as described in the previous section. Because phenomenography uses the interaction between a participant and a phenomenon as the unit of analysis, these two aspects of the study are described first.

3.4 Phenomenon

The phenomenon of interest for this study is engaging with ill-structured problems, which have been defined as having the characteristics of engineering work, including a lack of information given, ambiguity within the process, multiple possible solutions and flexible means of evaluating solutions. From these multiple characteristics, the possibility of multiple possible solutions was selected as a way to communicate the phenomenon to participants in a simple way without inducing bias due to particular language. Not only is the number of possible solutions a salient characteristic for distinguishing different types of problems as described above, but it is also a characteristic that can be easily communicated to first-year engineering students. Because problems with multiple possible solutions also tend to possess the additional characteristics outlined in the literature review, this handle is considered sufficient for accessing the phenomenon of interest.

Well-structured problems with one, checkable answer, such as end-of-chapter textbook problems are considered (and from this point on referred to as) Single Solution

Problems (SSPs). In general, these problems are also likely to present all the needed information (and only the needed information) and follow a well-known solution path. The focus of this study is instead on ill-structured problems with multiple potential solutions, or Multiple Solution Problems (MSPs), which were described in detail in the literature review.

In order to study a posed phenomenon, a distinction between the phenomenon (abstract) and situation (concrete) is made (Marton & Booth, 1997). For example, the phenomenon of engaging with problems with multiple possible solutions (abstract) can be experienced through the concrete engineering design projects (situation) that are a part of the curriculum for first-year engineering students. More detail regarding these projects is provided in the participants section. In order to gain access to the participants' experience of the chosen phenomenon, the interview protocol allowed students to describe a time they engaged with a problem with multiple possible solutions. This allowed students to choose any concrete experience that represents the phenomenon of interest. While the majority of students commented on a situation within their introductory engineering course work, reflections from high school engineering situations as well as robotics and other extra-curricular activists were also selected by participants.

Flexibility to allow students to select a salient concrete experience in the data collection was important. Because reflection on a concrete experience that the participant can recall and is willing to discuss openly elicits more variation in the data, they were not presented with a particular task during the interview. However, "the researcher might be primarily interested in exploring the variation in the learners' experience of a certain phenomenon and find that some of the learners are largely oriented toward the situation in which the phenomenon is embedded" (Marton & Booth, 1997, p. 83). This was addressed by asking participants to go beyond describing *what* happened to *why* it happened, which prompts abstraction of the concrete and insight into the students' perceptions of their experience of the broad phenomenon. In addition, I asked follow-up questions to prompt reflection and link their description of a concrete situation to the overall phenomenon. More details are provided in the data collection section. Next, an overview of the participants is included.

3.5 Participants

Participants were recruited from the first-year, introductory engineering courses at Purdue University ENGR 131, 132 and 133. ENGR131 and 132 are semester-long courses designed by Engineering Education faculty that are required for all first-year engineering students to complete the first-year engineering program requirements. ENGR 133 is a parallel course that is run through the Engineering Projects in Community Service (EPICS) programs. The designers of the courses purposely introduce problems with multiple possible solutions for the students to work on in teams throughout the semester. Additional details about the types of problem solving experiences that participants have in each of these classes is provided here.

These course designs are a demonstration of providing students with experiences engaging with problems with multiple possible solutions as "cornerstone design" rather than waiting until the later half of the students' training in the form of "capstone design." This is an appropriate context to demonstrate the phenomenon of interest and also within the context of engineering education. At the same time, these are all instances of how first-year engineering students experience MSPs, so sampling from all allowed me to capture variation across the different courses.

3.5.1 ENGR 131

This course is designed in order to provide first-year engineering students with a range of experiences. To start, students experience well-structured, closed-ended problems, which are expected to resemble some previous problem solving experiences that students are familiar with. For example, using Excel to determine which of two data sets has a higher mean. However, the next experience that students encounter is a Model Eliciting Activity (MEA). This provides students with again a well-structured problem (in that all the information is provided), but there are now multiple possible ways of approaching the problems, so it is open-ended. MEAs are "open-ended, realistic, client-driven problems set in engineering contexts requiring teams of students to create a generalizable (shareable, reusable, modifiable) mathematical model for solving the client's problem" (Diefes-Dux, Hjalmarson, Zawojewski, & Bowman, 2006). Finally, students in this course encounter a design project that is ill-structured, ambiguous, open-ended as well as context dependent. This course design strategically provides students with more ambiguous problem solving experiences that also increase in duration over the course of the semester. Because data was collected in a fall semester when there were predominantly sections of ENGR 131, the majority of my participants (19 of 27) were from this course.

3.5.2 ENGR 132

As a companion to ENGR 131, this course also offers students opportunities to work in teams on engineering problems. While there is some variation across sections, students have experiences (in addition to in ENGR 131 the previous semester) working in teams on open-ended problems. These problems include another MEA followed by a design project to create a graphical user interface using MATLAB. Students in ENGR 132 also have had additional time to digest and reflect on their experiences with design in ENGR 131. Only three of my 27 participants were from this course.

3.5.3 ENGR 133

Finally, ENGR 133 is a service-learning course, which requires students to work in teams on a wide range of problems. These problems are driven by a model of human-centered design and are ill-structured as well as open-ended. An added source of variation for participants from this course is that their projects are not tied to the academic calendar, but rather they are maintained through lasting partnerships within the community. As a result, depending on the semester that a student is involved in any particular project, they may experience a primary focus on a particular phase of the design rather than engaging with the entire design process from start to finish. A total of five of my participants were from this course.

3.6 Sampling

Purposeful maximum variation sampling was used for this study as is common in phenomenography (Bowden, 2000; Åkerlind, 2005a). This method of sampling aims to select participants that display different dimensions of chosen characteristics in order to select the most varied experiences possible (Creswell, 2008). This is according to the assumption that individuals with varied characteristics, interests or backgrounds are more likely to have varied experiences. Because the major purpose of phenomenography is to characterize the variation within the experiences of participants, maximum variation sampling will be used, drawn from a purposeful sample of first-year engineering students. This variation considered the following factors:

- age
- gender
- race
- student status (international/domestic)
- number of times enrolled in course
- (intended) major
- previous engineering experiences (e.g. high school engineering, robotics, summer camp)
- current course enrollment

Age was collected in order to ensure that participants were limited to students 18 years and older, as required by the IRB exemption. The gender of the participants was identified as a source of variation as previous research has shown that men and women vary in the way they perceive their competency when compared to their peers, which informs their self-efficacy and thus their experience (Hutchison-Green et al., 2008). Research has supported the effect of gender on experience with regard to attitudes towards engineering (Besterfield-Sacre, Atman, & Shuman, 1997), team dynamics (Laeser, Moskal, Knecht, & Lasich, 2003), and learning approaches (Stump, Hilpert, Husman, Chung, & Kim, 2011). Students race and immigration status were considered as students of ethnic minority have been documented as feeling like outsiders (Foor, Walden, & Trytten, 2007) and having different experiences than majority students (Besterfield-Sacre et al., 1997). The remaining factors were considered as likely to influence a students' experience based on if they were re-taking the class, their specific interest among the engineering disciplines and their previous exposure to engineering before college.

I did not ask students to submit any descriptions of the types of problems they had experienced, since I knew what sorts of problems they had been exposed to based on the course they were enrolled in.

3.7 Pilot Study

A pilot study was conducted in the summer of 2014. Because the quality of the interview protocol used strongly impacts the outcome of the study, this pilot is crucial to the research design (Åkerlind, 2005a). Five students enrolled in ENGR 132 over the summer were recruited and I conducted in-depth, semi-structured interviews that lasted about an hour. I then transcribed these interviews verbatim and conducted initial analysis in order to determine if my target participants did, in fact, describe their experiences engaging with problems with multiple possible solutions in ways that varied from one another. The pilot interviews confirmed the presence of variation as well as the ability of the protocol to elicit desired information about the phenomenon of interest. In addition, it served as practice to refine an appropriate interviewing technique (e.g. not introducing new content, not judging, probing for reflection) (Bowden & Green, 2005).

As a result of the pilot study, I confirmed that I should ask about students' experiences MSPs first, and then have students comment on SSPs. When I tried the protocol in the other direction, the focus of the interview shifted away from the key phenomenon of interest. Another example of what I learned from conducting pilot interviews was the importance of the introduction part of the interview. For example, I found it was very helpful to take adequate time to emphasize the purpose of the interview and how I was seeking to understand their perspective. I went so far as to prep the participants that the interview may be difficult because it would require them to think and articulate their own behavior, motivation, and experiences in ways that they might not have been pressed to share before. I also let them know that I would intentionally and repeatedly be asking follow-up questions with the purpose of better understanding their perspective. I also emphasized that there was no right or wrong answer, but rather I was looking to hear about their personal experience, thoughts and feelings.

As Bowden (2005) explains, this process is meant to improve and refine the researcher's interview technique, so the data collected here was discarded and new data was collected for the analysis in this study.

3.8 Human Subjects Approval

Before recruitment and data collection for this study began, I applied and received approval to conduct human subjects research from the Institutional Review Board at Purdue University. A copy of my exemption is included in Appendix A.

3.9 Participant Recruitment and Selection

As described previously, I recruited participants from across three first-year engineering courses at Purdue University in the Fall of 2014. These courses included ENGR 131, 132, and 133, all of which require students early in their engineering education to engage with problems with multiple possible solutions. I announced my study to students in multiple sections and provided them with the link to the survey to complete some demographic information and volunteer to participate in an in-depth survey regarding their problem solving experiences. This survey is included in Appendix B. From this, I received 77 completed surveys with individuals willing to participate in my study. The aim for number of participants was consistent with other phenomenographic studies: no less than fifteen and no more than thirty (Trigwell, 2000). Additional phenomenographic studies within engineering education have been completed with the following number of participants: 20 (Daly, 2008), 33 (Zoltowski et al., 2012). Using maximum variation sampling, I selected 30 participants and invited them to schedule an interview. Of these 30, 27 individuals scheduled and completed the interview process resulting in my satisfactory sample size of 27 first-year engineering students.

I conducted the interviews during weeks 12, 13, and 14 of the 17-week semester. This was to capture the experience of participants after they had had almost an entire semester in their class that included engaging with problems with multiple possible solutions without stretching into dead week or finals week.

A table summarizing the participants for this study is included in Appendix C. While this table includes the demographics for each participant, it is only intended to show that a sample including a range of differences was successfully recruited. This table should not be used to draw any sorts of correlations between a particular participant and the category that their experience informs. Table 3.1 conveys the variation that was obtained with in the sample for this study. The labels provide the category, count of students, and percent of population represented by that category.

Table 3.1. Demographic Variation in Participant Sample

Category	Groups	Count	Percent of Total Sample
Gender	Female	12	44%
	Male	15	56%
Race	White or Caucasian	17	63%
	Black or African American	1	4%
	Asian	6	22%
	Native Hawaiian or Other Pacific Islander	1	4%
	Prefer not to Identify	2	7%
Immigration Status	Domestic	22	81%
	International	5	19%
Enrolled Course	ENGR 131	19	70%
	ENGR 132	3	11%
	ENGR 133	5	19%
Intended Discipline	Aeronautics and Astronautics	1	4%
	Biomedical Engineering	2	7%
	Civil Engineering	3	11%
	Chemical Engineering	1	4%
	Electrical and Computer Engineering	6	22%
	Environmental and Ecological Engineering	2	7%
	Industrial Engineering	1	4%
	Interdisciplinary	1	4%
	Mechanical Engineering	4	15%
	Nuclear Engineering	1	4%
	Other	2	7%
Previous Engineering Experience	Yes	22	81%
	No	5	19%

For the intended discipline, undecided included one participant who was undecided and another who was considering transferring to business. All the engineering departments at Purdue were represented except for construction engineering and management and materials engineering.

3.10 Data Collection

I collected the data for this study through one-time, semi-structured, one-on-one interviews with individual participants. Interviews are the most common way of gathering data in a phenomenographic study (Bowden & Green, 2005; Åkerlind, 2012). These in-depth interviews lasted about an hour and captured a snapshot of students' experiences with problems with multiple possible solutions. It is assumed that these transcripts may only capture a fragment of a participant's view as well as that a single transcript may inform multiple possible ways of experiencing the phenomenon (Åkerlind, 2005b).

The ultimate goal of the interviews was to glean an understanding of the student's experience. Such an understanding was sought by conducting the interview on two levels. The first is a discussion of concrete examples, which are situations that represent the phenomenon of interest. This comes through students describing their experience (e.g. What happened?). I found that this was important to enable more productive reflection during the interviews. The next level is when the researcher moves the participant from a concrete recollection of a problem solving experience to a state of reflection about that experience (e.g. Why did they do that? How did it make them feel? What did they learn? How did they change?) (Marton & Booth, 1997). This is where the bulk of the data for analysis comes from. As Daly (2008, p. 41) explains, "the core of the interview is not the specifics of the example, but is the way the example is discussed, reflected on, and given meaning to, i.e. the way in which the participant shows their awareness of the phenomenon. What the person thinks about the experiences or has awareness of about the experiences is often more important than the description of the experience itself. Asking for an example provides a "medium" to support deeper discussion."

The structure of the interview protocol developed for this study is influenced by examining examples of other phenomenographic studies (Daly, 2008; Zoltowski et al., 2012). I also sought feedback from my committee as well as other phenomenographic researchers. An example of feedback that I incorporated into my protocol development was to include more broad questions and improvise with follow-up questions to better understand the experience of the participant as a whole rather than following a rigid structure. The interview protocol is presented in Appendix D; a brief rationale for including each section is presented here. In general, an emphasis is placed on developing questions that facilitate first a discussion of concrete problem solving experiences and then questions that prompt reflection (Åkerlind, 2005a).

Logistics: This section introduced the participants to what to expect for the duration of data collection. I informed them about the audio recording of the interview and had them select a pseudonym (I provided the first letter, but did not assign a name to allow them to chose a name of their preference with relation to their identity). I also complied with the IRB exemption by informing that their participation was voluntary and that we could cease the process at any point. Finally I asked if they had questions about the process.

Purpose: Here, I explained the over-all purpose of our conversation, to have a detailed discussion about their experiences solving problems with more than one potential solution. I let them know that I was interested in their experienced and that I wasn't looking for any particular that I was looking for, but would be interested in what they did, why they did that as well as what they thought and felt. I also alerted them of the dialogue-style of the interview and how I would be asking open-ended follow-up questions with the aim of understanding their perspective.

I provided myself with notes to remember to conduct the interview as free from judgment as I could and to continually seek clarification from the participant. For example, if they used the word leadership, I would ask them clarify what they meant by that. I would also follow their line of thought while always attempting to tie their perception back to how aspects of their experience were important in terms of problem solving.

Experience with MSPs: As typical in a phenomenography study, I began with an identical prompt for the participant to describe an experience they've had working on a problem with more than one solution. This allowed students to describe, in detail, their experiences. Once I had an idea of the project they participated in, I used follow-up prompts, which included what their experience involved and why they chose to go about engaging with an MSP in that way. I also asked about their role on the team and how they felt they had done well. The section of the interview operates on both a concrete and reflective level to understand the participants' experience.

Situated in Contrast to SSPs: This section allowed students to then comment on the familiar experience of engaging with problems with only a single solution. Placing this after our discussion of MSPs often elicited additional information about their perceptions of MSPs in comparison.

Reflection: The final aspect of the interview asked students to compare and contrast their experiences with SSPs and MSPs as well as reflect on what has been important about their experiences and what they have learned. This section was often where students began to synthesize what they had shared during the interview.

Conclusion: I wrapped up by allowing questions and thanking students for their participation. Once the recorder was shut off, about half of the students stayed to chat with me about my study and were even curious about studying engineering education. I felt that this was a positive sign that they felt comfortable and understood what their role was in the process.

At the conclusion of each interview, I filled out an interview reflection guide. A copy is included in Appendix E. The purpose of this was to allow me to capture my initial understanding of the overall experience of each participant through a brief summary. This was important as a guiding question for knowing when to conclude the interview if I felt I had a sense of what the experience had been like for the participant (Åkerlind, 2005b). It also was a way to capture nuances about the participant as well as difficulties in conducting the interview that I could reflect on to better prepare for the remaining interviews. I also noted my effort or difficulty in "bracketing" my own perceptions of the experience or the participant in aim of understanding their experience.

3.11 Data Analysis

Each audio transcript was transcribed verbatim. I transcribed nine of the interviews and the remaining transcripts (18) were completed by undergraduate researchers. Once each transcript was completed, I proofread it again along with the audio recording to check for accuracy. This also allowed me to build my familiarity with each interview and make sure that transcripts were consistent for further analysis.

During my initial round of analysis, I read each transcript as a whole and created a general summary of the way in which the participant described his or her experience engaging with MSPs. During this phase, I maintained an open mind in order to consider all possibilities to characterize the data, which was crucial to the eventual outcome space (Åkerlind, 2012). In addition to generating an overall summary of each transcript, I also noted quirks and assigned key words to each transcript. An example of a quirk would be if an interviewee seemed defensive or was particularly difficult to get to answer reflective questions. While this documentation did not count as a data source, it helped me to remain reflective of my own interview process as well as highlight a potential limitation of the study in that my data was only as good as the experiences I could gather from the participants. Upon the completion of each summary, I revisited the summaries that I created immediately after the interview to note the ways in which my summaries captured the feeling of understanding their experience that prompted me to end the interview. Alignment between the summaries validated my documentation and discrepancies were revisited.

With a summary of each transcript completed and key words assigned, I completed the first iteration of developing descriptive categories by sorting the transcripts into piles guided by the way in which participants describe their experiences engaging with MSPs. I continued to sort and re-sort while re-reading transcripts for clarification as necessary until I began to gain a clear understanding of why I had grouped transcripts together. Again, I focused on remaining open-minded to the possible meanings that could emerge from the data, as they were expected to evolve and be reorganized many times throughout the coding process (Åkerlind, 2012). I was also focusing on the development of the descriptions of the categories over any sort of logical relationship to reduce bias towards the categories (Åkerlind, 2005b). The result of this process is the following categories, presented in Table 3.2, in no particular order. Within the description, particular aspects of those descriptions from specific transcripts are noted by the transcript number in parenthesis.

Table 3.2. First Iteration of Categories of Description

Category	Participants Contributing	Description
1: Evidence/ Argumentation	3 Casey, 16 Pam, 5 Elliot, 22 Victoria, 25 Yellena, 15 Oliver	Solving MSP is about learning to provide evidence for your design. This is often in the form of argumentation, or talking in a persuasive way (22). Evidence also comes from research and consulting experts (15). A good design process requires evidence for each design decision (3). MSPs also require you to argue for your design within your group, or "selling" your idea (16, 5). Evidence for your design solution could also come from understanding the historical development of the product (15). Argumentation is required since MSPs have multiple factors to consider as well as multiple ways of evaluating designs; tools like decision matrix help lay out evidence for ultimate best design (3). "Hard core" calculations can be evidence for design decisions (3). Understanding the problem and providing evidence that you are invested also increases credibility (15). Being able to provide evidence for how you define the problem as well as design ideas show that you have a clear understanding, which also requires being able to communicate to a lay audience (22).
2: Coordination/Logistics	27 Anne, 18 Robert	MSPs require extensive communication from a coordinator to organize the team. Not all team members are capable of understanding the higher level picture (27). This includes logistics such as meetings (18) and communicating the common goal so that all team members are invested in working towards it and not wasting resources (27). You also need to communicate in order to share your ideas and make sure everyone understands what they need to be doing (18, 27). This sort of management takes away from your time actually designing (27).

Table 3.2. (continued)

Category	Participants Contributing	Description
3: Problem Definition	26 Zixi, 11 Karl, 10 Jack	The experience of solving MSPs centers on clearly defining the problem. From there, people see different things and the defined problem can be solved in different ways. Without a clear definition you cannot understand the problem, communicate rationale for design decisions or evaluate your decisions (26). The complexity of MSPs means that different people see the problem different ways and there are many aspects to consider (10). The way you define the problem must be relevant to the consumers/market (11). Your involvement in the MSP solution process may be limited by feedback from consumers (11) or the scope of your job within an organization (26). Finding relevant examples or talking to others with experience can help frame how to think about the problem (10). Once the problem is defined, the process is unclear--not linear like SSP process (10).
4: Working w/ others	2 Bentley, 12 Larry, 13 Matt, 17 Quinn, 19 Shaun	MSPs are experienced as working with others. Teammates are a source of feedback to improve your thinking, support you, and help you learn new skills (17), open your eyes to new perspectives (19), reduce the chance of a flawed design (12), and promote personal growth and be competitive (13). However, it may also impede progress--everyone thinks their own way is best (12, 13) or cause arguments (19). An individual's perspective is closely tied to their disciplinary training (12). Diversity is important in order to view the problem from different angles as well as different knowledge and skills (2). Engineering comes second to establishing trust amongst your team (2). Personal skills that allow you to work with others are important so you can be confident to be successful with MSPs (2). This experience may influence you towards engineering management; you need to trust your judgment and the judgment of your team (19). You can’t get to the top without help from others (17).
5: Grades vs. Learning	4 David, 7 Geoff, 8 Ha, 21 Ulsa, 23 Will	This experience centers around navigating the requirements of the classroom (getting a good grade) and meaningful learning for the future. There was an emphasis on determining what the instructors wanted, especially when requirements were modified or unclear (4, 8, 23) and recognition that going through the process was of higher importance than the actual detailed design (21). The experience was necessary to prepare for the real world, but felt forced and frustrating (7). The projects were too complex compared to what was assessed (21). There was tension between recognizing the need to gain autonomy and feeling as though you knew how to earn a good grade (23). Uncertainty resulted in just trying to make it look good to earn points (4, 21). Aspects of the design process (e.g. decision matrix) were manipulated retroactively to satisfy classroom constraints (8, 23). MSPs are good preparation for the mindset needed to be an engineer that there can be more than one answer--this builds confidence (8, 21). This mindset includes accepting that you’re on your own and will come easier with time (23).

Table 3.2. (continued)

Category	Participants Contributing	Description
6: Design as you Build	20 Tiffany, 24 Xin	These experiences of MSPs are more focused on designing as you build. Hands on experience is important. Ideas are evaluated through a devil's advocate (20) or an informal listing of pros and cons or personal reaction to the idea as exciting or not (24). It's important that everyone be able to physically contribute (20). MSPs allow you to work with others and use creativity, debate which design is best (20). Experts provide important perspective (20,24). MSPs need teams because individuals have different skills (20) or angles of seeing the problem (24).
7: Using Creativity	6 Fran, 14 Neil	MSPs are an opportunity to use creativity (which allows you to link constraints to solution) (14) and personal interests to inform design. They are more fun. Designs should make sense to you (14), be informed by the user's needs (6) as well as be professional in the sense that they are clearly communicated to others (6). Your interpretation of the design problem is a function of your prior experience (6). Engineering design is challenging and attractive because it is dynamic and you can always build on prior art in new ways (6). MSPs have continued progress, don't have to scrap anything because you can make anything work (6, 14). Leadership is needed so you don't stall with discussion only--group should formally establish leadership (14).
8: Irrelevant (same as SSP)	1 Alex, 9 Izzy	MSP experience is irrelevant--ultimately the same as SSPs...require you to consider what is being asked, determine approach, and get to work (1) or find a solution (9). The project is just another thing you have to do for class (9). The experience includes having to carry your team and they went along with whatever he said (1). Team helps to disperse pressure of project, but also means you may have to compromise on your ideas (9). The design project was insignificant since it doesn't relate to your interests (1,9), although teams is good experience (1). Projects are intended to introduce different engineering disciplines (9). A good MSP considers all aspects and doesn't make false assumptions (1). Other aspects of coming to college and gaining independence are more important for promoting personal growth (9).

During the creation of these first categories, I didn't use any sort of hierarchy to inform the categories, although I did note some potential overlap between categories. At the conclusion of developing these categories, I began to feel that one possible theme of expanding awareness might be communication. For example, I noticed that the categories varied in the way the experienced the purpose of communication within solving MSPs. The categories that seemed to be the most clear were Categories 1, 2, and

4. Categories 3, and 5-8 seemed less clear and I expected that those latter categories may undergo more drastic change in following iterations of analysis.

Next, I re-read all the transcripts and documented the excerpts that were in alignment with their initial categorization as well as those that were not. However, this exercise resulted in focusing on the "noise" within the variation and caused me to lose sight of working towards considering the participants' experiences as a whole and in comparison to the others within the sample. I tried to sort the transcripts thinking about communication, but it proved difficult and I wasn't able to develop categories that I felt were progress form the initial sorting. So, I met with others to discuss what I was seeing in the data, and the idea of communication, or discourse (including more than verbal communication such as information gathering) was agreed to be a theme that had emerged based on the first iteration of analysis. Using this as a guide, I revisited each transcript and read it in its entirety while maintaining a lens of discourse. By that, I mean I was guided by focusing on understanding the participants' experience by the following questions:

- How are students' experiences with MSPs framed by discourse?
- What types of discourse are they using?
- Who are they engaging with discourse with?
- What do they perceive as the function of their discourse?
- Who benefits from their use of discourse?

This resulted in the second iteration of descriptive categories, still with a focus on the categories rather than their logical relationship. Like the first iteration, these are presented in no particular order, or without a logical relationship, in Table 3.3.

Table 3.3. Second Iteration of Categories of Description

Category	Participants	Description	Borderline cases that also contribute
1: Get through the process	8 Ha, 10 Jack, 24 Xin, 20 Tiffany	Discourse is used to coordinate the completion of the project. Everyone should contribute to the work and engage with the team enough to do their fair share and earn his/her grade (8). Relevant examples or experiences of others (discourse outside the team) can help you identify an adequate design (10, 24). Design ideas can be talked about and decided on as you build (24). It is most important to get through the process and complete the project within constraints rather than really making an innovative design (10).	9 Izzy, 18 Robert...both in *5: Utilize different perspectives*
2: Explain your idea	1 Alex, 5 Elliot, 14 Neil	These participants used discourse to explain their ideas and get their teammates to understand (14). This may be because they were the only one contributing ideas (1) or because they used effective communication to convince their team to select their idea as the team goal (5).	
3: Understand each other and work together	2 Bentley, 26 Zixi, 27 Anne	These experience describe using discourse that revolves around making people feel comfortable enough to contribute (2) and creating a shared vision that everyone is invested in (27). It is important to understand the context or way that people are defining the problem in order to evaluate their contributions (26).	21 Ulsa in *8: meet course requirements*
4: Use differences to deal with complexity*	7 Geoff, 12 Larry	These participants explicitly talk about the fact that MSPs are complex and that they engage with other individuals on their team can help to cope with this complexity. This may be a successful effort where differences are valuable (7) or could prove difficult if individuals will not compromise and let go of one-size-fits all solutions (12).	
5: Utilize different perspectives*	6 Fran, 9 Izzy, 13 Matt, 17 Quinn, 18 Robert, 19 Shaun, 22 Victoria	Here, discourse is used to learn about the other perspectives that your teammates hold. You can learn from them through gaining feedback on your ideas (17). Engaging in discourse also provides you with access to different ways of thinking that may be better than yours (6, 9). The experience of engaging with MSPs illustrates that people have different ways of viewing problems (13, 18, 22) and this can lead to personal growth (13). It also allows you to build on the ideas of others (20).	

Table 3.3. (continued)

Category	Participants	Description	Borderline cases that also contribute
6: Convey evidence for design	3 Casey, 16 Pam, 25 Yellena	The main purpose of discourse within the context of MSPs is to learn to provide evidence through argumentation for your design. This includes having an understanding of why you made all the decisions that you did and being able to defend those decisions (3, 25) and being able to talk about your project in a persuasive way (16).	6 Fran, 13 Matt and 22 Victoria...all three in *5: utilize different perspectives*
7: Design for user	11 Karl, 15 Oliver	Discourse is about gaining an understanding your target audience so you can improve on an existing design (15) or focusing on creating a product that is relevant for your audience (11).	
8: Figure out what course requires	4 David, 21 Ulsa, 23 Will	These experiences with MSPs included discourse aimed at understanding the requirements of the project. These may have changed over time as the professor added them (4). Expectations were not made clear from the beginning of the course (4, 23). An understanding of what was wanted only became clear once the process had been gone through--details were added retrospectively to 'give them what they want." (23) Beyond determining what was wanted for the course, learning was also facilitated by trying to understand why those things were needed (21).	

*Note: These might seem like the same thing. However, Category 4 is about using differences to solve the problem, while Category 5 is more focused on how differences contribute to your own learning and personal growth.

By examining the borderline cases that resulted from this round of sorting transcripts, I realized that several transcripts seemed to contribute to the idea of utilizing all perspectives. This brought to light that just a single axis of variation did not capture the key variation sufficiently, so I began to think about how these categories could be further teased apart. With additional reading and sorting, I identified another possible axis of variation, which was the purpose of engaging with the project. Separating out the use of communication from the purpose of engaging with MSPs led me to my third iteration, presented in Table 3.4. This iteration also began to include the logical relationship along with the description of the category.

Table 3.4. Third Iteration of Categories of Description

Category	Participants	Description
1: Completion	1 Alex, 4 David, 10 Jack, 20 Tiffany, 24 Xin	The focus of MSPs is to complete the task at hand and gather information from multiple sources in order to understand what needs to be done. Group members contribute by completing work.
2: Transition/ Reflection	8 Ha, 21 Ulsa, 23 Will	MSPs are a chance to go through a new experience and learn why that experience is important in your training as an engineer. This approach includes reflection beyond just completing the task, understanding why you were asked to do so.
3: Input your Ideas	5 Elliot, 6 Fran, 14 Neil	MSPs allow you to have some autonomy in the problem solving process through conveying your own ideas. This includes creativity and effective communication so others understand your perspective.
4: Coordinate People	18 Robert, 19 Shaun, 27 Anne	MSPs require you to coordinate others. You need understand their perspectives so you can facilitate consensus and keep your team on track towards reaching the common goal.
5: Utilize Perspectives to Improve Design	2 Bentley, 7 Geoff, 12 Larry, 26 Zixi	MSPs reveal that others have different strengths, skills, and prior knowledge. The goal is to use these different perspectives in order to address as many aspects of a complex problem as possible. You also need to work to understand the different perspectives so that you can evaluate the reasoning.
6: Personal Growth	9 Izzy, 13 Matt, 17 Quinn	MSPs expose you to the different skills, and perspectives of your teammates, which expands your thinking and broadens your understanding of the problem.
7: Design for Others	11 Karl, 15 Oliver	MSPs are an opportunity to solve a problem in a way that is relevant and useful to the consumer.
8: Develop Evidence, Argument	3 Casey, 16 Pam, 22 Victoria, 25 Yellena	MSPs bring together multiple perspectives so that a better solution can be found. The goal of that process is to develop an argument for your design decisions and be able to defend your design to others.

I also developed a draft of the logical relationships that were beginning to emerge based on seeing some categories as inclusive of others. That outcome space is presented in Figure 3.1 with the x-axis representing the theme of expanding awareness "benefactor of experience" and the y-axis representing "purpose of communication."

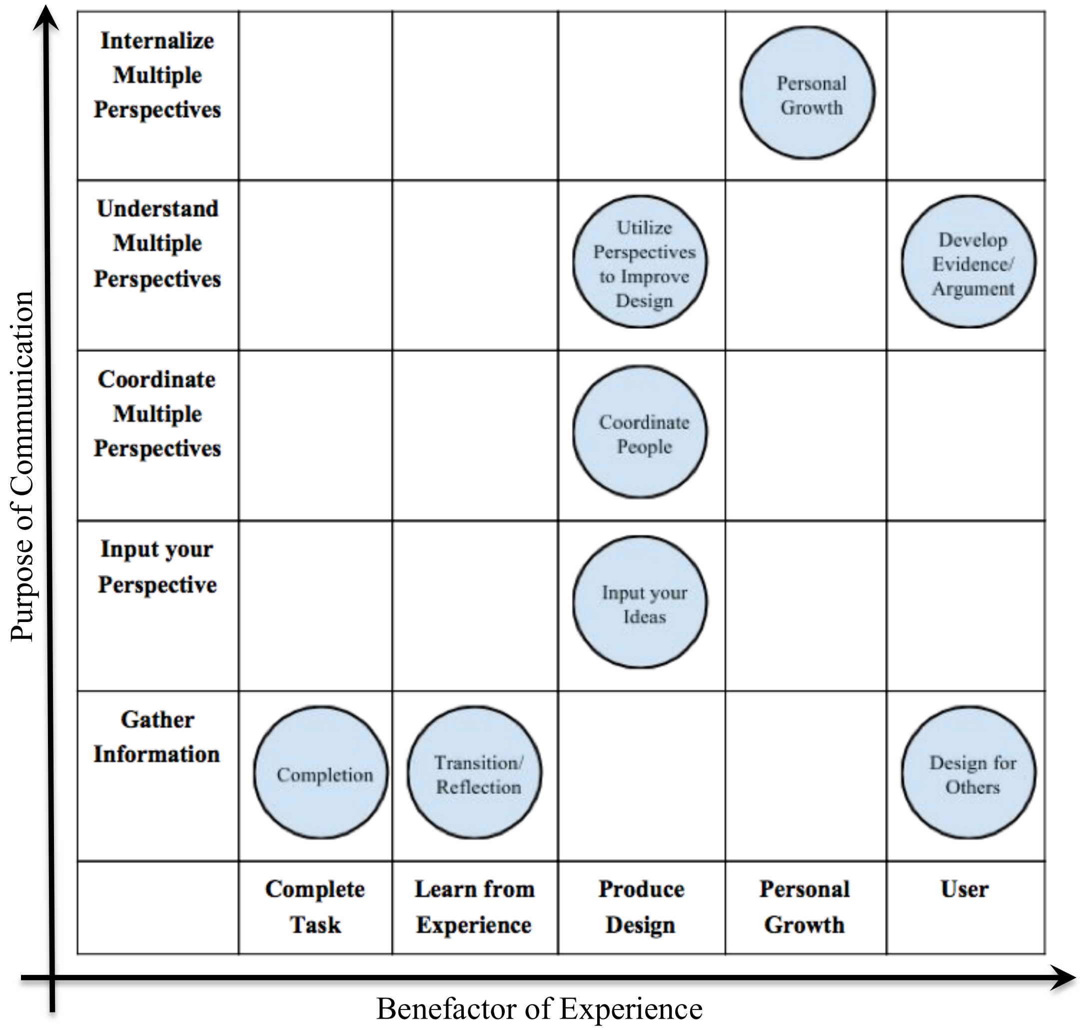

Figure 3.1. Third Iteration of Categories of Description In First Outcome Space

I sought feedback through discussion on this iteration of categories as well as the updated categories of description. One major outcome was that Designing for Others was really still about the design, so it could be moved two spaces to the left (gather info about user to try to design for their perspective). I was still uncertain about how the group Develop Argument/Evidence fit in with these themes of expanding awareness that I had discovered. While I knew I had to remain open and not fit it in just to have a pretty picture, I also kept in mind that phenomenographic analysis requires the researcher to discern "noise" from "signal," and so if the main things that really captured variation across *all* the transcripts were the ways in which participants conveyed their perceived goal of the project and their purpose for communicating, I decided to return to the data again to determine what was the "signal" for these transcripts in the Develop Argument/Evidence group that made sense with the outcome space.

In order to develop the fourth group of categories, I re-read all the transcripts for evidence of how they informed a proposed category and used that to guide me in thinking about how to describe the categories in a more useful way as well as when a transcript really belongs in a different (or new) category. This included pulling relevant excerpts, which can provide concrete data for others to use as they play the role of Devil's Advocate for my interpretation of the fourth iteration, presented in Table 3.5. I also went back to the unmarked electronic copies of the transcripts so that I was not influenced by previous highlighting and notes on the hard copies of transcripts.

Table 3.5. Fourth Iteration of Categories of Description

Category of Description (Engaging with MSPs is…)	Summary
Category 1: Completion (Alex, David, Izzy, Jack)	Engaging with MSPs is centered on completing the task in the classroom setting. The focus is not on developing a design or using the design process, but rather on seeking information that will enable the student to successfully complete the assignment. Relevant information includes clarifying what the instructor wants, discussing with students who have previously completed the course. This approach views working with others as an opportunity to divide and conquer and lacks an appreciation of teammates as sources of knowledge.
Category 2: Learning (Ha, Ulsa, Will)	Engaging with MSPs is still classroom-centric, but this way of experiencing is aimed at learning from going through the experience. While the participants do seek information that will allow them to successfully complete the task, they also reflect on why they are being asked to engage with this sort of problem and how it is a transition from SSPs in their past. There is a tension between wanting enough information to ensure a successful project and realizing that they need to transition to working more independently.
Category 3: Just-in-time Design (Tiffany, Xin)	Engaging with MSPs is focused on trouble shooting and creating an artifact. Design decisions are made without an explicit process and typically as they are needed, informally. Information sought includes expert opinion.

Table 3.5. (continued)

Category of Description (Engaging with MSPs is…)	Summary
Category 4: Iterate for User Needs (Karl, Oliver)	Engaging with MSPs is an opportunity to design something that is relevant to a particular user or market. Design is aimed at improving an existing product based on user perspective.
Category 5: Exercise Personal Influence (Elliot)	Engaging with MSPs is an opportunity for the participant to influence the design decisions based on their own ideas. They are focused on conveying their own perspective to others. It is important to communicate your ideas effectively so that others will understand and your ideas will "win" against the other perspectives within the team.
Category 6: Organize (Larry, Neil, Robert, Anne)	Engaging with MSPs requires the resolution of multiple perspectives. This includes coordinating logistics and establishing a common goal for the team to work towards. While multiple perspectives are needed, it is difficult to bring them to a single solution.
Category 7: Optimize (Bentley, Fran, Geoff, Pam, Zixi)	Engaging with MSPs allows you to utilize the multiple perspectives on defining a problem and designing a solution for that problem. As a team, you can share your perspectives and determine the best idea or combination of ideas to form a solution. As a designer, you need to make an effort to listen and consider the ideas of others—they can be valuable to optimizing your design.
Category 8: Justify (Casey, Victoria, Yellena)	Engaging with MSPs means working with multiple perspectives to generate an optimized design. The process isn't meant to just lead to a final design, but rather to remain cognizant of the process you are using, which serves as justification for your design. This is necessary to convince others why your solution is better than the other potential solutions and to "sell" or communicate your design to others, including non-technical individuals.
Category 9: Growth (Matt, Quinn, Shaun)	Engaging with MSPs exposes you to multiple perspectives, which not only improves your design, but also expands your own thinking. You learn from your team in a way that stays with you after the design is completed. MSPs are an opportunity for personal growth in becoming an engineer.

These categories were then reorganized into a second iteration on the outcome space, which is shown in Figure 3.2. In addition, I began developing descriptions of the relationships between the categories, and that part of the process is summarized in Table 3.6.

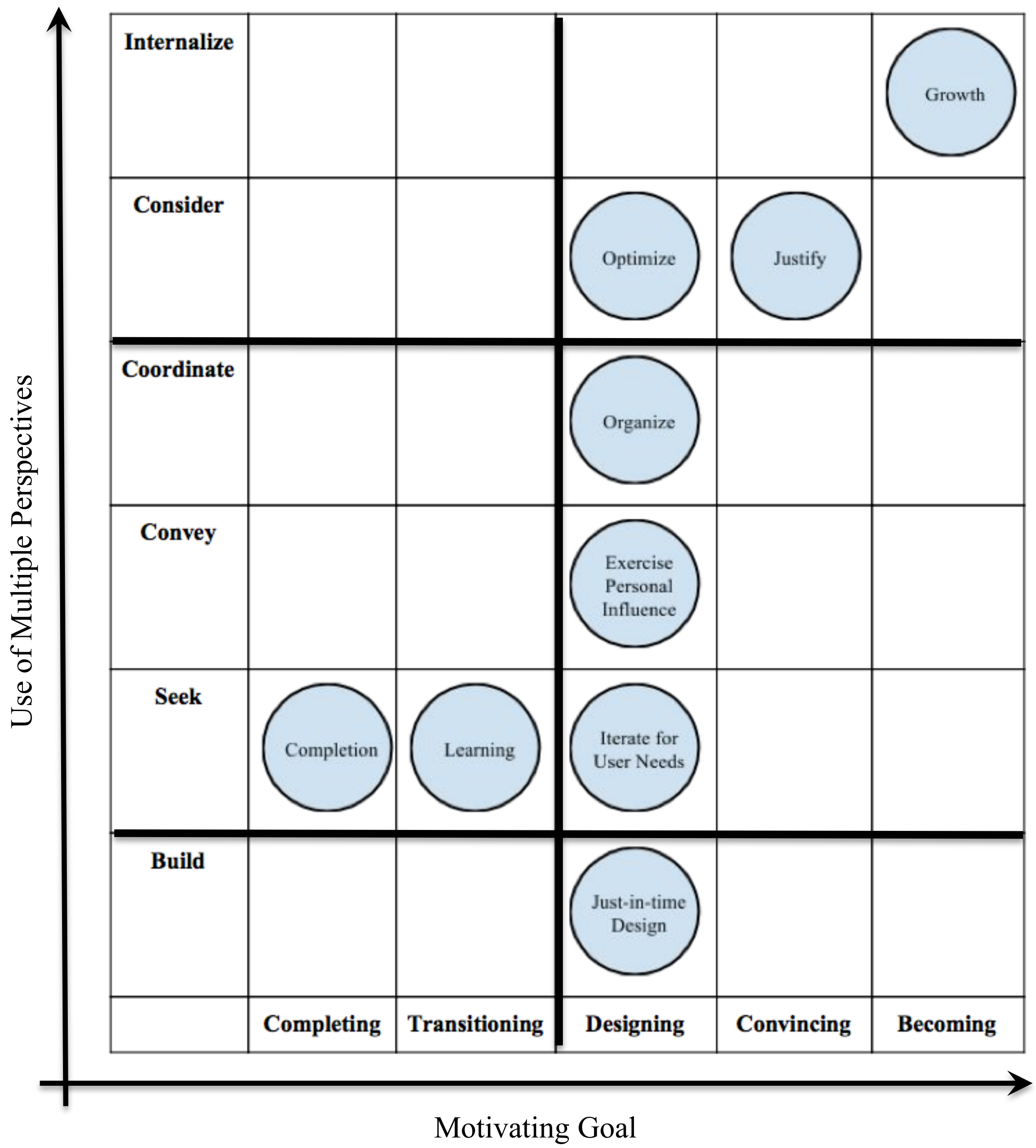

Figure 3.2. Fourth Iteration of Categories in Second Outcome Space

Table 3.6. Second Outcome Space Category Relationships

Category or Transition	Description of Relationship Related to Outcome Space
1	Task-oriented lacks a focus on the design as well as the value of multiple perspectives. The focus is completing the classroom assignment.
1 → 2	Learning is still not design, but it moves beyond completing the task through reflection on the task as an important learning experience. Going through the process is for the sake of learning, not designing.
3	Just-in-time Design is focused on trouble shooting and creating an artifact. While this is considered design, the use of multiple perspectives is used in a more linear process of making decisions as needed during the design process.
4	User-oriented design focuses on trying to understand the user perspective in order to improve a product or design something relevant.
4 → 5	Rather than seeking the opinion of the user, the designer can also influence the process with their own design ideas.
5 → 6	Beyond contributing your own perspective, the focus of this category of experiences centers around coordinating all the perspectives within the design team.
6 →7	This transition crosses the threshold from the multiple perspectives being something that needs to be controlled or organized to an asset. Now, multiple perspectives are to be utilized in order to create a design that could not be generated without the team's diverse perspectives and ideas.
7 → 8	Multiple perspectives are still utilized, but beyond the design, the understanding of those perspectives facilitates the development of a design rationale. This justification is needed as evidence to defend your design decisions and convince others that your design is the best.
8 → 9	This transition indicates the integration of multiple perspectives that go beyond improving the design to improving the individual. They internalize the multiple perspectives that they are exposed to and carry those changes with them into future engagement with MSPs.

At this point in the analysis, I pulled quotes to support and represent the key ideas that I had found to hold each category together as well as distinguish the categories from one another. This synthesis was then presented to three different engineering and design education researchers who have all conducted phenomenographic studies. I utilized their expertise in the Devil's Advocate role (Bowden, 2000) in order to receive specific feedback on my findings such as to reconsider a category that only contained a single participant and also to reconsider the real theme of expanding awareness I was observing with regard to motivations vs. ways of dealing with complexity. These extensive conversations prompted a final round of analysis, and the categories and outcome space stabilized. The result are the findings of this study presented in Table 3.7 as the fifth and final iteration of descriptive categories in my phenomenographic analysis. The corresponding final outcome space is shown in Figure 3.3.

The major changes with this final iteration were to simplify the outcome space to meet the goal of generating something that is of practical use to engineering educators. I was also challenged to push on maintaining a category that consisted of only a single participant, and as a result Elliot's transcript was re-read and I recognized the ability of the Organization Category to represent the major theme of his experience engaging with MSPs. Additionally, I was able to see that the Just-in-Time Design category was really about iterating to improve a design, which could be combined with the Iterate for User Needs category in order to create the final category of Iteration. An experienced phenomenography also encouraged me to try to use single words where possible to label the outcome space, because while phrases may seem to capture more, they still cannot capture all the nuances I am aware of (further description is necessary), yet they make the figure less clear.

Table 3.7. Fifth and Final Iteration of Categories of Description

Category of Description (Engaging with MSPs is…)	Summary
Category 1: Completion (Alex, David, Izzy, Jack)	Engaging with MSPs is centered on completing the task in the context of a classroom setting. The focus is not on developing a design or using the design process, but rather on seeking information that will enable the student to successfully complete the assignment. Relevant perspectives to understand include clarifying what the instructor wants or discussing with students who have previously completed the course. This approach views working with others as an opportunity to divide and conquer and lacks an appreciation of teammates as sources of knowledge. Students attempt to eliminate ambiguity in order to make the problem more well-structured.
Category 2: Transition (Ha, Ulsa, Will)	Engaging with MSPs is still classroom-centric, but this way of experiencing is aimed at learning from going through the experience. While the participants do seek information that will allow them to successfully complete the task, they also reflect on why they are being asked to engage with this sort of problem and how it is a transition from SSPs in their past. There is a tension between wanting enough information to ensure a successful project and realizing that they need to transition to working more independently. They acknowledge the need for ambiguity in engineering, and they articulate their future transition into accepting it.

Table 3.7. (continued)

Category of Description (Engaging with MSPs is…)	Summary
Category 3: Iteration (Tiffany, Xin, Karl, Oliver)	Engaging with MSPs is focused on trouble shooting and creating or improving an artifact by iterating on a design. Design decisions are made without an explicit process and typically as they are needed, informally. Relevant perspectives that help to navigate ambiguity include expert opinion as well as user needs. Once these perspectives are known, the designer can iterate on the design to improve it. This way of experiencing crosses an important threshold into accepting ambiguity within problem solving.
Category 4: Organization (Elliot, Neil, Robert, Anne)	Engaging with MSPs requires the resolution of multiple perspectives. This includes coordinating logistics and establishing a common goal for the team to work towards. While ambiguity is accepted and multiple perspectives are viewed as a function of that ambiguity, it is difficult to coordinate bringing the contrasting views to a single solution. Time spent navigating multiple perspectives should be kept to a minimum in order to make progress towards a solution.
Category 5: Collaboration (Bentley, Fran, Larry, Geoff, Zixi)	Engaging with MSPs allows you to utilize the multiple perspectives to defining a problem and designing a solution for that problem. As a team, you can share your perspectives and determine the best idea or combination of ideas to form a solution. As a designer, you need to make an effort to listen and consider the ideas of others, who may be right despite their difference from you. This way of experiencing crosses a threshold to valuing the perspectives of others as they can be valuable to optimizing your design.
Category 6: Reasoning (Casey, Pam, Victoria, Yellena)	Engaging with MSPs means working with multiple perspectives to generate an optimized design. However, unlike Category 5, the result of this process isn't just a final design, but rather a design with accompanying justification. This way of experiencing shifts to accepting ambiguity to embracing it as a useful part of the process. By navigating both the ambiguity and the multiple perspectives, the design team can develop reasoning for their decisions. This is necessary to convince others why your solution is better than the other potential solutions and to "sell" or communicate your design to others, including non-technical individuals.
Category 7: Growth (Matt, Quinn, Shaun)	Engaging with MSPs and their ambiguity is valuable because the experience exposes you to multiple perspectives, which not only improves your design, but also expands your own thinking. You learn from your team through internalizing your understanding of their varying perspectives, and that understanding stays with you after the design is completed. MSPs are an opportunity for personal growth in becoming an engineer.

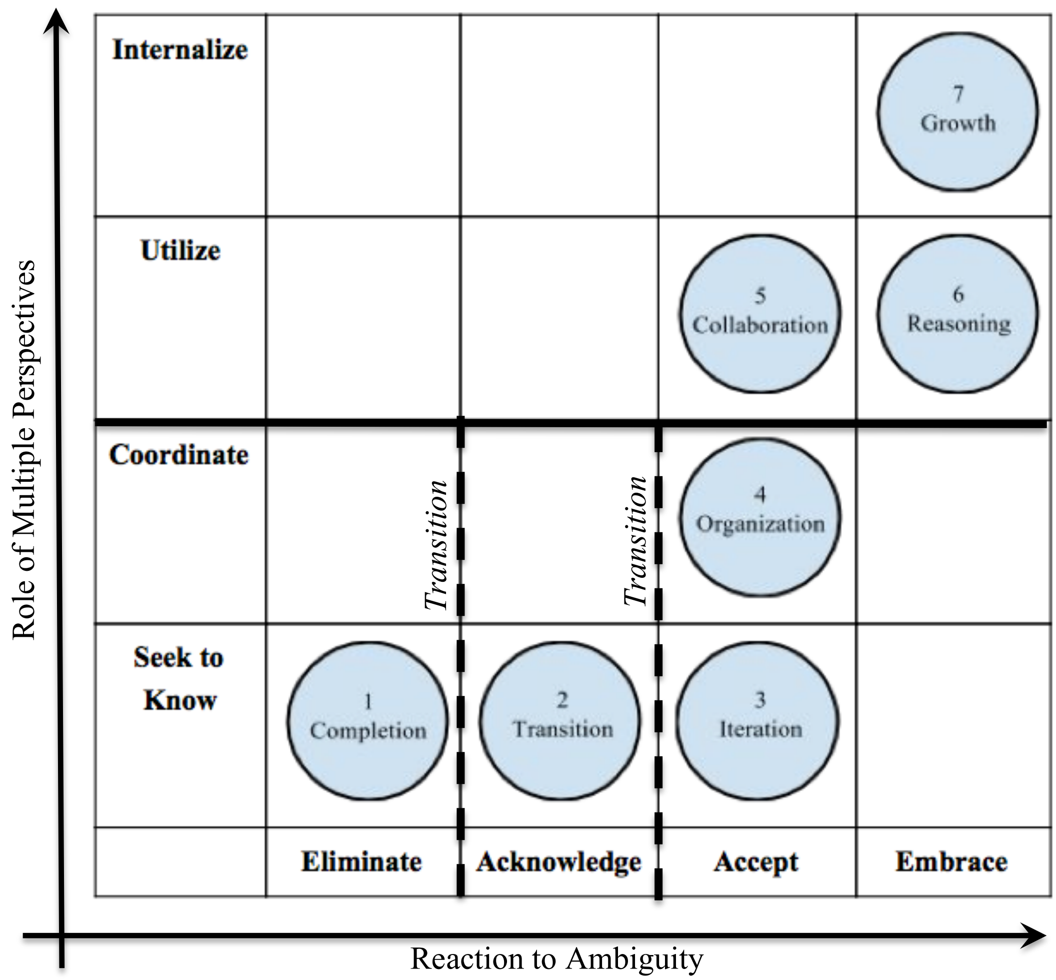

Figure 3.3. Final Outcome Space of Ways of Experiencing MSPs

Further descriptions of these categories, the differences between them, and the resulting outcome space along with data excerpts to demonstrate my interpretation of the transcripts is included in Chapter 4.

3.12 Validity and Reliability

Due to the qualitative nature of this research, generalizability or an objective (statistical) measure of validity or reliability of the methods and findings is not the goal, but rather a trustworthy collection of the data and analysis is needed. At the discretion of the reader, the findings may or may not be considered transferrable depending on how closely another population and context aligns with the phenomena and participants of this study.

3.12.1 Qualitative Validity

Åkerlind's (2012) offers of the two types of validity common in phenomenographic studies: communicative and pragmatic. While the communicative aspect of validity deals with being able to defend the process that was used to develop the outcome space, the pragmatic aspect of validity deals with the results being useful to the community. I worked to ensure both through the process of this study. To start, I conducted a pilot study to refine the interview protocol technique to solicit data about the phenomenon of interest. Throughout the interviews, I worked to ask questions that were not leading to the participants and I refrained from introducing content or my perspective into the conversation. Transcripts were transcribed verbatim, so the entire conversation was available for context throughout the analysis process.

I maintained a detailed documentation of the entire analysis process including reflective details on my thinking and the influences of conversations with others. These conversations came from intentional communication with other researchers who have worked in the first-year engineering space. This provided communicative validity along the way as I shared and received feedback on my process. I addressed pragmatic validity by aiming to produce results that are useful for practitioners as a way of understanding how the students in a beginning level engineering course experience engaging with problems with multiple possible solutions.

3.12.2 Process Reliability

To begin, I used an identical introduction and prompt for each interview. These interviews were conducted within a short time period of only two weeks to reduce variation in time between participants. Reliability was also demonstrated through clear documentation of each iteration of the analysis procedures throughout the research process, which has been likened to a quality management system in an engineering context (Walther, Sochacka, & Kellam, 2013). Inter-rater reliability for the coding of the data was not calculated because all the interviews will be conducted and coded by one researcher. Marton (1988) describes that for phenomenography, the process doesn't need to be replicable, but categories need to be usable with some inter-rater reliability. This level of usability was ensured by working with the committee and relevant members of the community related to first-year engineering to develop an outcome space that was meaningful and grounded in the data. Similarly, Åkerlind (Åkerlind, 2012) explains that the phenomenographic approach does not search for a categorization scheme that is "right," but rather defendable. The next chapter presents my findings as well as the empirical evidence for the results of my phenomenographic analysis.

3.13 Researcher Positionality

Phenomenography is an exploratory qualitative research approach that operates from an interpretivist framework; the researcher serves as both the interpreter of data and constructor of categories. Whether it is explicitly stated or not, the researcher's bias always affects the research design and process. "The way in which we describe the variation reflects our, the researchers', value judgments about what counts as a good, or a better, understanding of a text, of a problem, or whatever. Value judgments cannot be empirically grounded, but they can be argued" (Marton & Booth, 1997, p. 107). In order to argue for the hierarchy established through my analysis, I provide details of my rationale in Chapter 4. In addition, the on-going feedback that I received from experienced researchers was a way to continue to build the rationale in a way that was verified by others with experiencing working with first-year engineering students on problems with multiple possible solutions.

In this study, the goal was to understand the experience of students through their eyes, without judgment or in comparison to the experience of the researcher. I continuously attempted to bracket my own understanding of what it means to engage with problems with multiple possible solutions. In general, the "second order perspective adopted requires the researcher to take the place of the respondent, trying to see the phenomenon and the situation through her eyes, and living her experience vicariously. At every stage of the phenomenographic project the researcher has to step back consciously from her own experience of the phenomenon and use it only to illuminate the ways in which others are talking of it, handling it, experiencing it, and understanding it" (Marton & Booth, 1997, p. 121). This was done throughout the collection of the data as well as the analysis process.

CHAPTER 4. RESULTS

4.1 Introduction

The results of this phenomenographic study included seven qualitatively different ways that first-year engineering students experienced problems with multiple possible solutions. These categories included the following: completion, transition, iteration, organization, collaboration, reasoning, and growth. In addition to the categories, this work also generated a logical relation between these categories, which is represented as an outcome space. The major axes of variation in this figure are reaction to ambiguity and role of multiple perspectives. These results were directly informed by empirical evidence captured in the interview transcripts from 27 first-year engineering students at Purdue University. This chapter provides detailed descriptions of the categories and their logical relations along with evidence from the transcript to support my interpretation.

4.2 Overview of Results

An overview of the seven descriptive categories that describe the qualitatively different ways that first-year engineering students experience engaging with problems that have multiple possible solutions is provided in Table 4.1. It should be noted that these categories are not full representations of the perceptions captured in the data, but rather they capture a range of perceptions of similar ways of experiencing generated from an amalgam of the transcripts contributing to that category (Barnacle, 2005).

Table 4.1. Summary of Ways of Experiencing MSPs

Category of Description (Engaging with MSPs is…)	Summary
Category 1: Completion (Alex, David, Izzy, Jack)	Engaging with MSPs is centered on completing the task in the context of a classroom setting. The focus is not on developing a design or using the design process, but rather on seeking information that will enable the student to successfully complete the assignment. Relevant perspectives to understand include clarifying what the instructor wants or discussing with students who have previously completed the course. This approach views working with others as an opportunity to divide and conquer and lacks an appreciation of teammates as sources of knowledge. Students attempt to eliminate ambiguity in order to make the problem more well-structured.
Category 2: Transition (Ha, Ulsa, Will)	Engaging with MSPs is still classroom-centric, but this way of experiencing is aimed at learning from going through the experience. While the participants do seek information that will allow them to successfully complete the task, they also reflect on why they are being asked to engage with this sort of problem and how it is a transition from SSPs in their past. There is a tension between wanting enough information to ensure a successful project and realizing that they need to transition to working more independently. They acknowledge the need for ambiguity in engineering, and they articulate their future transition into accepting it.
Category 3: Iteration (Tiffany, Xin, Karl, Oliver)	Engaging with MSPs is focused on trouble shooting and creating or improving an artifact by iterating on a design. Design decisions are made without an explicit process and typically as they are needed, informally. Relevant perspectives that help to navigate ambiguity include expert opinion as well as user needs. Once these perspectives are known, the designer can iterate on the design to improve it. This way of experiencing crosses an important threshold into accepting ambiguity within problem solving.
Category 4: Organization (Elliot, Neil, Robert, Anne)	Engaging with MSPs requires the resolution of multiple perspectives. This includes coordinating logistics and establishing a common goal for the team to work towards. While ambiguity is accepted and multiple perspectives are viewed as a function of that ambiguity, it is difficult to coordinate bringing the contrasting views to a single solution. Time spent navigating multiple perspectives should be kept to a minimum in order to make progress towards a solution.
Category 5: Collaboration (Bentley, Fran, Larry, Geoff, Zixi)	Engaging with MSPs allows you to utilize the multiple perspectives to defining a problem and designing a solution for that problem. As a team, you can share your perspectives and determine the best idea or combination of ideas to form a solution. As a designer, you need to make an effort to listen and consider the ideas of others, who may be right despite their difference from you. This way of experiencing crosses a threshold to valuing the perspectives of others as they can be valuable to optimizing your design.

Table 4.1. (continued)

Category of Description (Engaging with MSPs is…)	Summary
Category 6: Reasoning (Casey, Pam, Victoria, Yellena)	Engaging with MSPs means working with multiple perspectives to generate an optimized design. However, unlike Category 5, the result of this process isn't just a final design, but rather a design with accompanying justification. This way of experiencing shifts from accepting ambiguity to embracing it as a useful part of the process. By navigating both the ambiguity and the multiple perspectives, the design team can develop reasoning for their decisions. This is necessary to convince others why your solution is better than the other potential solutions and to "sell" or communicate your design to others, including non-technical individuals.
Category 7: Growth (Matt, Quinn, Shaun)	Engaging with MSPs and their ambiguity is valuable because the experience exposes you to multiple perspectives, which not only improves your design, but also expands your own thinking. You learn from your team through internalizing your understanding of their varying perspectives, and that understanding stays with you after the design is completed. MSPs are an opportunity for personal growth in becoming an engineer.

The logical relationship that was developed along with the descriptive categories as a part of the phenomenographic analysis is presented in Figure 4.1.

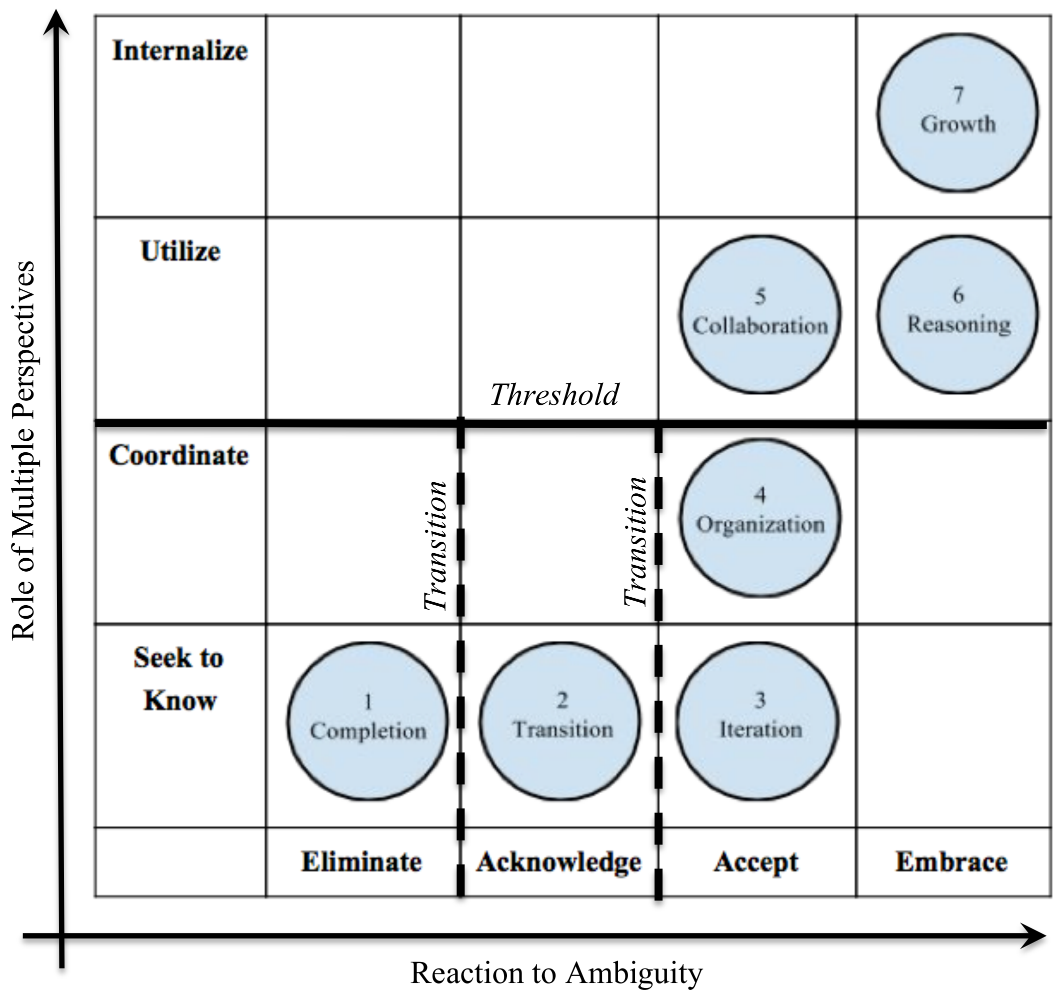

Figure 4.1 Final Outcome Space of Ways of Experiencing MSPs

Also, before providing a more detailed description of the categories along with data to support the interpretations, the transitions between the seven categories are summarized briefly in Table 4.2.

Table 4.2 Summary of Relationships between Categories of Description

Category or Transition	Description of Relationship Related to Outcome Space
1	The experience is task-oriented and attempts to eliminate ambiguity by seeking information and adding structure to the problem. The focus is completing the classroom assignment.
1 → 2	This move is characterized by a transition into awareness that engineering work is ambiguous, and uses reflection to move beyond completing the task to viewing the experience as important and necessary. The process is aimed at learning to accept ambiguity in problem solving.
2 → 3	Here, another transition occurs as students accept ambiguity and turn their focus towards seeking information that can help them iterate on a design for the sake of improving it. Improving it may include making something physical work or designing something in accordance with user needs.
3 → 4	This category begins to shift the way that students see the role of multiple perspectives when engaging with MSPs. The focus is on the coordination of those perspectives in order to establish a common goal and make progress.
4 → 5	A significant transition occurs by crossing the threshold into experiences that value the multiple perspectives within the design team. Now, students describe experiences of collaborating with others to generate better solutions.
5 → 6	Now, in addition to using multiple perspectives to navigate ambiguity, the ambiguity is now an asset as coming to understand each others' perspectives produces evidence for the design that can be used to defend decisions made during the design process.
6 →7	The final category also embraces ambiguity as a benefit of the experience, but shifts from utilizing the perspectives of others to allowing those perspectives to alter the participants' own perspectives. This is the most comprehensive category as the experience does not end when a solution is reached, but the process affects the designer's future problem solving perspectives.

Next, I present the distribution of participants organized by the category they belong to. I also include salient characteristics, full details of their demographics can be found in Appendix C. The purpose of Table 4.3 is not to suggest that correlations can be established based on these groupings, however trends could be used to inform future research. For example, while the participants were generally distributed and there are exceptions to these trends, it can be observed that no EPICS students contributed to the two least comprehensive categories and no ENGR 132 students contributed to the four most comprehensive categories. Also, the students with no previous exposure to engineering generally contributed to less comprehensive categories.

Table 4.3 Distribution of Participants within Categories of Description

							Previous Eng. Experiences	
Category	Pseudonym	Sex	Race	Student Status	ENGR Course	Intended Major	Yes	No
1: Completion	Alex	Male	White	Domestic	131	ChE	X	
	David	Male	White	Domestic	132	IE	X	
	Izzy	Female	Native Hawaiian or Other Pacific Islander	Domestic	131	IDE	X	
	Jack	Male	Asian	International	132	ECE		X
2: Transition	Ha	Female	Asian	International	131	EEE	X	
	Ulsa	Female	White	Domestic	131	CE	X	
	Will	Female	White	Domestic	131	BME		X
3: Iteration	Tiffany	Female	White	Domestic	133	ME	X	
	Xin	Male	White	Domestic	131	ECE	X	
	Karl	Male	Asian	Domestic	132	BME		X
	Oliver	Male	White	Domestic	131	AAE/Business	X	
4: Organization	Elliot	Male	Black or African American	Domestic	131	AAE	X	
	Neil	Male	Prefer not to Identify	Domestic	131	AAE	X	
	Robert	Male	White	Domestic	131	ECE	X	
	Anne	Female	White	Domestic	133	AAE	X	
5: Collaboration	Bentley	Male	White	Domestic	131	ABE	X	
	Fran	Female	White	Domestic	131	ME	X	
	Larry	Male	White	Domestic	133	CE	X	
	Geoff	Male	White	Domestic	131	ME	X	
	Zixi	Male	Asian	International	131	ECE	X	
6: Reasoning	Casey	Female	White	Domestic	131	CE	X	
	Pam	Female	Prefer not to Identify	International	131	ECE		X
	Victoria	Female	Asian	Domestic	133	ECE	X	
	Yellena	Female	White	Domestic	131	NuclE	X	
7: Growth	Matt	Male	Asian	International	131	ME	X	
	Quinn	Female	White	Domestic	133	EEE	X	
	Shaun	Male	White	Domestic	131	Undecided		X

4.3 Categories of Description

This section provides a more detailed description of each category of description along with evidence for this description from the transcripts that contributed to each category. The excerpts included are only portions of entire transcripts, so while I did provide some context to them, they are unable to capture the experience described during the interview in its entirety. Each category is considered a qualitatively different way of experiencing engaging with problems with multiple possible solutions. As described in Chapter 3, these categories were developed through iterative phenomenographic analysis of whole transcripts from 27 first-year engineering students. While participants expressed large amounts of variation in sharing their experiences, these categories describe the key ways in which their experienced differed. Also, participants' description of their experiences may inform more than one category, but because transcripts were sorted as wholes to remain focused on the overall way in which they describe their experience(s), each transcript has been listed with the category that best and most completely describes it.

4.3.1 Category 1: Completion (Alex, David, Izzy, Jack)

A summary of this category is that engaging with MSPs is centered on completing the task in the context of a classroom setting. The focus is not on developing a design or using the design process, but rather on seeking information that will enable the student to successfully complete the assignment. Relevant perspectives to understand include clarifying what the instructor wants or discussing with students who have previously completed the course. This approach views working with others as an opportunity to divide and conquer and lacks an appreciation of teammates as sources of knowledge. Students attempt to eliminate ambiguity in order to make the problem more well-structured.

The experience that contributed to this category emphasized their drive to focus on completing the task. This included seeking information that can lead the team towards the simplest way of getting to an adequate solution and working through the problem quickly. For example, in their discussion of working on designing an eco-shopper for ENGR 131, both Alex and Jack describe their intentions of identifying an acceptable design and then driving the design team towards a solution in the easiest way possible. It was as though finding the right example or information would allow the students to eliminate the ambiguity of the problem.

> Alex: Um, yeah. We so like we got our task and we pretty much, I mean immediately jumped online to, I don't know. Because that's sort of like I guess the easiest way to sort of go about it, see if anything's already happening and then see if we can either improve on that or base off of that existing thing. Um, so we went online. Um, pretty much chose our design from the beginning. … I think we all just sort of, like, saw it and sort of agreed that that was one of the best solutions. … Um, like I found it and I was like, "this is a pretty cool idea." And they, um, they just sort of agreed.

> Jack: Uh, so, we were just like brainstorming a lot of ideas in the beginning. Can we do bike? Can we do a bus? Or something like that? Uh, which one do you think is easier? And then we, like, vote for doing which and we exchange our reasons why we should do this, why this takes less time than the others. And then we reduce our ideas to the bike. And then we'll just distribute our work. Like you do the .ppt, and you Google some information, and I'll write something.

The experiences described in this category also sought information from their instructors or other students who have gone through the class in order to understand how to complete the task and satisfy the requirements. In particular, David describes the frustration of trying to determine how to satisfy the course requirements and not being given clear directions from the instructional team while working on a design task in ENGR 132. Also, their descriptions of working within their team were more focused on dividing the work or the disappointment in team members not contributing.

Jack: Uh, I would ask, like, other classmate, or some people who have taken that class and ask them for ideas. And they would, like, give me some advice. Say, oh, it's not a hard problem. Actually, you don't need to do this much, you have to do something, this this this. And then, oh, that sounds not a lot of work. And then I will, like, be a little more confident than before.

David: We're trying to do it with our approach, and they're not liking that approach, so they change the criteria on us. And they kind of did it in a sly manner. They were like, milestone four and five they were like, "oh we won't grade milestone four, but we'll just give you a lot of feedback because milestone five will be just like the second draft of it, the final version of it. Just work off that feedback." And in between they gave us this new criteria and they're like, "Well we'd like to see more math models that are not linear." And we're like, "wait, this was never the criteria in the beginning." So they just kind of slid it in there, which made it kind of terrible to do milestone five, because between that we just had to scrap all of our ideas and kind of start over, which is, that was kind of difficult.

David: You feel like you're hacking at a tree with a little hatchet. But you're trying to make it look good...it's like you kind of feel like your project is just supposed to look good and it's supposed to be, when they're going through the rubric it needs to look good. … They don't give you a rubric too, which is a huge frustrating thing in this class. Like the rubrics kind of show up after it's graded. That's on like every homework. Every like, like on the projects they give you the outline of what they want, kind of like a deliverable of what they're looking for. But then, when that criteria came up, I just right away started asking the TAs like, "so where was this criteria from?" And they were like, "oh we discussed this in a meeting that we had to have more complicated things." I also talked to the professor too and he's just like, "yeah we're just looking for this." And finally it was whenever I talked to the GTA he said, he's like, "yeah this is what they want

> now. This is what we're going to have to see." … It's kind of like a system, and you feel like that's half the battle is just figuring out what the system is.

Another quality of the experiences in this category was a lack of belief that the experience was meaningful beyond completing the task for the sake of the course requirements. Students did not perceive their experience engaging with MSPs as characteristic of engineering work. Izzy, Alex, and Jack all express their perceptions of their experiences engaging with MSPs in ENGR 131 in this way.

> Izzy: Well we're all here for the same reasons, so we have to get it done. Um, cause it's the assignment. … I mean the problems just don't really have a purpose [beyond exposure to different engineering fields] … I don't know, it's not like my the first thing that I would like, talk to someone about

> Alex: This design project I think is stupid. I think it's just like a waste of time. It's like incredibly irrelevant, so.

> Jack: Actually, I think engineering 131 is not important. It's something not really useful. I think the most, the only important, the only useful part of it is Excel skills and Matlab skills. Other kinds of concept is too conceptual, too abstract, for us students to understand. Or even apply. So…

Overall, the experiences of engaging with MSPs that contributed to this category were focused on completing the task at hand through seeking information that could lead to an adequate solution. The students found avenues of eliminating the ambiguity that existed when presented with MSPs to expedite the completion of the task. The experience was not described as meaningful to them.

4.3.2 Category 2 Learning (Ha, Ulsa, Will)

A summary of this category is that engaging with MSPs is still classroom-centric, but this way of experiencing is aimed at learning from going through the experience. While the participants do seek information that will allow them to successfully complete the task, they also reflect on why they are being asked to engage with this sort of problem and how it is a transition from SSPs in their past. There is a tension between wanting enough information to ensure a successful project and realizing that they need to transition to working more independently. They acknowledge the need for ambiguity in engineering, and they articulate their future transition into accepting it.

To start, the participants in this category explicitly identify the purpose of their experience as going through the design process, not as the result of their design work. All three of the participants whose transcripts contributed to this category explicitly said that they perceived the intention of the design experiences within ENGR 131 were expose them to the design process.

> Ha: I understand the point of the class—it's not like we give out so complicated, advanced design. They just want us to go through the procedure and then want us to work on it as a team. So, it is not important that, it is not as important, like, we have to think about something really advanced or really innovative, we just have to think of something and then we work on it as a team. We, like, treat it as a real project and that's like good enough.

> Will: Ok so I think they were more concerned about the design process than what you actually came up with.

> Ulsa: I know they were more concerned about going through the actual process than what your final solution was. … So I know there's some groups who just like, they had what their final thought would be from the beginning, but we tried to follow what everyone was doing because we knew that that would help our grade in the end, even if it felt weird going through this whole process just to get

> to the final idea. But it was interesting that like the original ideas we thought of wasn't what we ended up as. And that was kind of their goal, I guess, to get us to think that way.

Although the experiences that informed this category described the experience as a way to learn about the design process, they also felt the pressure of earning good grades. In contrast to the previous group, they describe seeking information to understand the course requirements along with an understanding of the motivation behind those requirements in terms of their own development. Will describes her experience of working through a design task driven by the instructions she was given, and finding it difficult to deal with the ambiguity since she still felt the pressure of the grade riding on the project.

> Will: They also didn't really like, explain each step very well and then when they finally did it was like, the class before it was due, so like then everyone was kind of like frantically trying to figure it out. So I didn't really feel like… like we went through it, but we roughly went through it and so like when you're trying to describe it in like a project, I feel like you didn't really go through the design process you're just trying to put down the answer and trying to figure it out. Not making up stuff but kind of just like expanding on stuff more than what you actually did. So you give them what they want. … I feel like it's helpful in a way to know that like you know you're going to have to figure it out yourself. They're not…you can't just ask the teacher a question all the time. Umm. So in a way I feel like it's helpful. But then in a way, I feel like it's like….I feel like then they're not giving us enough information. Umm…to do what they want. Cause it also like still like for a grade.

Similarly, Ulsa describes navigating the course requirements; her experience includes turning things in, and so she feels she has to understand not just what is wanted, but why those deliverables are expected so that she can earn the grade and also understand the reason for what she is being asked to do.

> Ulsa: Okay, so I like, really like understanding what all of the qualifications are, like I said, I'm the one that turns things in. So that has allowed me to understand maybe more of what they want us to get done. And not just follow what everyone else is doing. So maybe other people would have had the experience of just like, the brainstorming and what we're going through without really understanding what's expected at each step. Because I have to know what's expected to get things turned in. … So I had to understand why we were doing this and everyone else was just like let's get these sticky notes on here, you know, whatever. So I had to kinda understand this is what we need to get done to show the professors that we earned this grade, or, you know. That's what's expected. … Otherwise it kinda seems pointless to me. Like that's what they want us to do. I'm not just doing it because they want us to do it, but I like to understand what's going on.

This category of experience also included an explicit discussion of how they were undergoing a necessary transition towards understanding how to engage with engineering problems with increased independence, which was interpreted as an acknowledgement of ambiguity in engineering problem solving, while there was still difficulty in accepting or navigating that ambiguity. Towards the end of the interview where participants were asked to reflect on what it has been like to engage with MSPs, all three of the following excerpts capture their awareness of their transition. Will and Ulsa articulate the transition as it relates to their previous experience in high school and Ha ties her transition to her future in the workplace.

> Will: I think coming from like high school and coming from a different mindset of engineering, you know you're kind of always told we want this and this and this and this and this, so it's just a lot different than what we're used to. … It's weird [laughs]. I mean, I guess like that's not like that's just not what we've done for like the past 12 years of schooling, or whatever, so it's just, it's a lot different than what you're used to. But, it's not a bad thing. Like you're gonna have to learn eventually how to do stuff on your own and not be told what to do all the

time. It’s just like...it’s kind of a transition, I guess, to know that…and it’s just it’s also kind of like you hope you’re doing the right thing but you’re not completely sure. … I guess it’s just, like I said before, it’s just…it’s a really big transition from like what were used to, so I don’t know, like it’s nothing that like any of us are used to throughout high school and stuff. And I feel like since, I guess, I don’t know--it feels like you can say they don’t explain it very well, but there isn’t really a way to explain it, like, you need to do this by yourself.

Ulsa: Okay, and engineering was something completely new for me, I never had an engineering class in the past. It’s forced me to work with groups for more than just one like small project. Now there’s these big projects and the whole class is groups, and it’s, like I said, it’s a new kind of mindset, you’ve always heard that engineering is group work, well what does that really mean to be, like, on a group for a real project? More than just like, in high school the only group experience I had, was like, you’re in English class or something making a two minute PowerPoint presentation or something like that. That wasn’t, you weren’t working on anything technical with other people.

Ha: Mmm, like, I think that it’s more, when we, like after graduate when I get a job it will be more like, like the multiple solutions thing. Because, then, when they tell us to do something in the homework, we are certain that there’s only one right answer. But when we work, like on the job, when they tell us to do something, we don’t really know, like, we don’t know that there’s only one answer because they are…you don’t know what it’s like, so, I feel like working on the group with the multiple solutions project is more, like helped me prepare, I mean not prepare the experience, but prepare about the mindset that it will be like that. You just don’t know what the answer is.

The next category crosses the threshold into accepting ambiguity and working in different ways to navigate through it.

4.3.3 Category 3 Iteration (Tiffany, Xin, Karl, Oliver)

A summary of this category is that engaging with MSPs is focused on trouble shooting and creating or improving an artifact by iterating on a design. Design decisions are made without an explicit process and typically as they are needed, informally. Relevant perspectives that help to navigate ambiguity include expert opinion as well as user needs. Once these perspectives are known, the designer can iterate on the design to make improve it. This way of experiencing crosses an important threshold into accepting ambiguity within problem solving. Transitioning from Category 2, where students are still displaying difficulty in accepting ambiguity, participants who described their experiences in ways that contributed to this category express their acceptance of ambiguity and some of the challenges it brings to problem solving. This category also shifts in focus from a classroom context to a focus on the design itself.

> Tiffany: I like solving problems [laughs]. Um, being presented with like something that doesn't work or something that is challenging, I guess, doesn't make me mad or upset, it's like, ooh good I get to work on this. Because, I don't know. I don't know examples, like clothing breaks, or a necklace I made breaks, I'm like cool, now I get to figure out how to fix it.

> Karl: I mean, just the fact that knowing that there are multiple solutions to a problem makes it very different because you never know if you have something that'd be a good solution to the problem, or what the people who are looking for the solution, if that's actually what they're looking for.

> Oliver: I think it's more fun to analyze the pros and cons of everything and figure out what's actually going to be the best. Whereas with a math problem if you mess up and you don't get the right answer and it's really frustrating because you just want the right answer. Or if you get the right answer it doesn't seem as kind

> of fulfilling as if you worked on a project with multiple choices and you came up with that choice because you think it's the best.

In terms of perceptions of multiple perspectives, outside information is still sought in order to inform the design process. This includes seeking information to better understand both the problem and the solution. Information is no longer assumed to be provided by the teacher. Instead, the experiences in this category include seeking information from individuals with relevant experience as well as the perspectives of the users. Xin mentions that he would seek information from his instructor about the requirements for participating in a design team building a Rube Goldberg machine.

> Xin: if we had a question about the project, what requirements we needed or like maybe advice on how to go about building something, we'd ask him and he would usually help us out.

As another example, Xin completed an Eagle Scout project to build benches, and in that case he describes interfacing with an experienced work worker to directly inform his design.

> Xin: So I'd say between there it kinda took some visualization with like some other adults who kinda knew more about that kinda thing. Like so umm, I'd kinda go to them and tell them what's what the project details were and they'd like bounce ideas off me and then I'd kinda came up, or they kinda helped me come up with a design that would kinda fit the requirements. So like an example of that would be my grandpa has extensive like, hands on experience.

While these examples demonstrate the experience as including seeking information to inform the solution space, the experiences that inform this category also describe seeking information to define the problem space. This included Xin's description of a fairly simple problem description from a local community member to identify the general problem space in a way that did not provide all the information needed, but rather allowed him to use his judgment.

> Xin: So umm so the teacher who I talked with who kinda gave me the project umm or the project details umm, kinda specified that she wanted some like benches for kids to sit on in like a courtyard. Umm. And besides that, it was up to me to like actually make them, however I thought best.

Oliver's transcript describes at length the importance of seeking information from the user in order to better understand the problem space, which included understanding the current design of a shopping cart as well as the perspective of people with experience in the context of supermarkets for his experience with the eco-shopper design task.

> Oliver: So far it's involved figuring out what's wrong with the current shopping cart, asking people what they like and dislike about the current shopping cart and then just coming up with a bunch of different ideas of potential shopping carts and testing it against each idea and asking people if they would like it or not like it. … Because we're trying to make it more eco-friendly and better for the consumers. So we need to figure out what is wrong with the current model so we fix those problems along with making it more eco-friendly and easy to use. … And a guy from Meijer came in, the manager for a local Meijer came in, and he was talking about city audiences, city consumers and how they had problems sometimes carrying it on a bus or, say, a taxi cab taking it back. Because he worked at a large grocery store earlier in his career. … And then, also with the Meijer guy, we asked him a lot of questions about what problems they ran into or what was beneficial about the current system so we could keep that in place as we went on with our new idea…. he had, like, 23 years of experience in the business so he brought a lot of knowledge to this project, so we just wanted to tap into his resources and figure out all that he's been through because he's worked in city and rural and different companies. So he had a lot of knowledge for us.

Oliver also described how his experience with the eco-shopper design project in ENGR 131 required him to consider the perspective of a user different than himself. Experiencing this process caused him to realize that a problem space can be influenced by who is considered as the user.

> Oliver: Okay, I'll just start with me. I'm from a rural town, so, and we just have a local grocery store. So, thus, wide open spaces, big aisle lengths or aisle width. And then there's some other guys from bigger towns around the country, so they have smaller aisle widths because they have to get more in there for everybody. And then the parking lots smaller or they have to walk on the sidewalk to get to their apartment. Smaller area. And they would struggle with the bags, if they carried their groceries in the bags, because they couldn't take the shopping cart, they would have to struggle with that. But I wasn't used to that because I could just throw it in the car right that's right outside because I can't walk to the grocery store. So it was a lot of different aspects. A lot of people walk to the grocery store, whereas I'd never dream of doing that.
>
> Oliver: Yeah, a lot of people, when the project first came out. Okay we're going to redesign the shopping cart. It's been in use for 50 years and there hasn't been a big uprising to change it. So we were like "okay, why are we doing this?" it doesn't need changed. It's like the wheel. The wheel's not broken, don't fix it. Or don't reinvent the wheel. So from that stand point it's frustrating. I mean, it's a fun project but it is also kind of frustrating thinking okay, this shopping cart works fine. If people really wanted to change it we would have changed it a while ago. But then looking at our idea of going upstairs, the current shopping cart, just carrying the bags up, it doesn't work. It's kind of a back and forth constantly. We got to analyze it. And like, okay, we got to stop thinking about changing the general shopping cart and think about providing a product that you can call a shopping cart but actually does a lot more than a regular shopping cart.… I didn't

really think there was a problem with it, because it’s been around so long, it seems to work fine for everybody, but then once we got into it more, we figured out that there actually are problems and hindrances for different consumers, depending on where they are. So I guess going forward, if there’s a problem, or not a problem, I can think of it in an aspect of maybe there are problems for people, there’s just not enough people to really make it a big problem for people to notice. So I can think of that, think of an idea that’s working and an aspect that’s maybe not working for a certain group of people and I can think about how to fix it.

Once information was gathered regarding the problem or solution space, the design could then proceed in a logical manner. Xin and Karl both commented on how once more information was gathered, the design process was then largely logical and straightforward.

Xin:…which ever concepts had more pros without overweighing cons kinda, uh it kinda just reduced itself into that. Into the final solution.

Karl: Um, it’s just like I said earlier, because I think it’s, the most important thing about working on a problem with multiple possible solutions is that the problem is clearly defined. Because if the problem isn’t clearly defined, then you’re not gonna get a solution that matches that criteria, the, like results criteria that you’re looking for. So it’s, once you have the problem clearly defined I think it’s, I mean it’s obviously important that you’re going the right way because you’re trying to get to an answer. But that just kind of happens once you have the problem clearly defined because then you know which way to proceed after that point.

Another major aspect of this way of experiencing MSPs is the emphasis on iterating on an existing design. This involves generating some sort of improvement on a design, and these improvements are motivated by a desire to make things work, to stay relevant, and to provide continuous improvement to a design solution. To start, in Xin's discussion of working in a team on a Rube Goldberg project, he discusses his experience of improving a design as you go and being able to complete the implementation of the design. Tiffany also describes an experience focused on iterating towards improvements in design as you are working.

> Xin: So we kinda wanted to make sure that we weren't spending too much time like just brainstorming. We kinda did more of the ideas as we kept building it, we kept trying to improve it. Like we kinda had a base idea and then we kinda just improved on it as time went on. Up until like, the deadline. … We kinda just spent in class time just like to build it and kinda just like get at each other's ideas and how we could build it better, how we could make sure everything was stable, nothing would break after one use. Umm. So then as it progressed, as everything got to where it needed to be, Umm after consulting with the groups and finally being able to connect it all, we were able to test it a couple times. Sometimes pieces wouldn't work right so those had to be fixed and…so overall it became successful.

> Tiffany: Oh gosh. Um, role, like, I guess I can say I played devil's advocate a lot, just like pointing out the details that's like, no that wouldn't work 'cause of this thing. Yeah. … Um, because like if we'd then, just made a design, that like the details weren't considered, then we would have to start all over again. … So you can point out which details of it might not work and like which parts of it could be improved and so like by, you know, somebody building off of your idea and being like, okay so if we did this other thing, couldn't that make it better? You can be like, no it wouldn't, and discuss why.

The motivation to identify the needs of a user and iterate towards addressing those needs was discussed as a strategy to be competitive as well as provide a useful design to consumers. Karl describes the technology he is developing as an entrepreneur and the importance of continually improving his design through iterations.

> Karl: But, from my experience, I don't think there is a final product, especially if you want to stay relevant. … So, I think that's why iterations, or steps, are very important because they force you to keep on top of the game, make sure you're doing something that's relevant and make sure you're doing something that benefits your consumers. … I think it's important to be relevant because it's, when you're working on a problem with multiple solutions, at least personally, I think it's easy to lose sight of the big picture sometimes. And for me, the big picture is to not be a one-and-done kind of, just like, get a solution out there, forget about it. It's get a solution out there, and then make it better the next year. Make it better the year after that. And, the way to do that is to be on top of the, like the tech trends, or whatever problem you're, sector you're in, um, and so that's why I think it's very important to be relevant in working on a problem with multiple solutions.

Karl goes on to compare the way he's experienced design in the classroom at Purdue to what he perceives to be more real-world examples.

> Karl: Um, I think it's important to have iterations, and I don't think, I think iterations is an interesting word, especially going through Purdue's engineering program because they always kind of focus on iterations as being an end, like, a means to an end. Like, you just do an iteration and then you just keep doing iterations until you get to a final product. But, from my experience, I don't think there is a final product, especially if you want to stay relevant. Uh, it's, I mean, I don't, I guess if you, like, look at it in terms of the last 10 years or whatever, like, the Walkman. They didn't really stay relevant because they never really iterated on that device. I mean, they might've added cool new features. I never had a Walkman, but, yeah. So, like, their irrelevant, so I think that iterations are very important in order to just, like, have a piece of the pie. … So, I think that's why

> iterations, or steps, are very important because they force you to keep on top of the game, make sure you're doing something that's relevant and make sure you're doing something that benefits your consumers.

A similar awareness of the need to iteratively improve a design is captured by Oliver's description of a high school project that he experienced aimed at implementing a recycling program for his school.

> Oliver: So once we analyzed that we were able to fix the problem we were trying to fix, which brought up more problems and we were able to fix that. So it was kind of just continuous patchwork with the analyzing…So just problems that we don't even think of come up, or that you don't even think of come up and you've got to fix them, otherwise it won't run smoothly, and eventually it will quit.

The next category moves from seeking the perspective of others, such as instructors, experts, or users to recognize that there are multiple perspectives within the team of students working on the problem with multiple possible solution.

4.3.4 Category 4 Organization (Elliot, Neil, Robert, Anne)

A summary of this category is that engaging with MSPs requires the resolution of multiple perspectives. This includes coordinating logistics and establishing a common goal for the team to work towards. While ambiguity is accepted and multiple perspectives are viewed as a function of that ambiguity, it is difficult to coordinate bringing the contrasting views to a single solution. Time spent navigating multiple perspectives should be kept to a minimum in order to make progress towards a solution.

To start, this category of experiences was informed by a lot of discussion on establishing a team goal, which includes conveying your own ideas, and the clarifying that goal so that everyone is working towards the same end. This is important so that the team members are all invested in a single goal that has been agreed upon through communication out of the multiple perspectives within the team. Communication also includes norm setting so that the team is able to progress in their work. Elliot describes his experience as hinged on being able to effectively communicate his ideas during a design project in ENGR 131.

> Elliot: Well, it's, like I don't usually freeze, or I'm pretty good at relaying my ideas and painting the picture for them in their minds for them. Like, I don't have to show them a picture to make them see what I'm seeing in my mind. Like, I'll have the picture in my mind and I'm basically describing the picture to them while I'm presenting. And, it, uh, made presenting a lot easier. Because, like by the time I would be presenting it, I would know exactly what I want to do and, I mean, by the time that we would present it, I would actually like know the virtual design, where everything would go. And uh, I kind of put a lot into my ideas and I would go pretty deep into it. So then by the time I presented I knew a lot about the topics, and usually that's why my ideas were chosen because I was more committed to it, I suppose you could say. Like, I wanted my building to be the prettiest [laughs] and the most functional of course [laughs].

Anne describes the importance of taking those individual ideas and facilitating group consensus on one of them, which was the focus of her experience as the team lead for her high school robotics team. Elliot elaborates on how this consensus of the team was powerful and even allowed them to manipulate their methods of evaluating a design. Robert's early experience with a design task included conducting a vote to establish a team goal.

> Anne: Um, and so that's kinda, you don't want one person thinking, 'I really think this,' and then you don't want another person, you know, 'I really think this,' without that communication being resolved up front. … Um, 'cause sometimes there would be like, a very 25 percent of the team would want this although the other 75 percent would be all for another, but then that 25 percent, they might say, oh, I do…I see how we would succeed and this is well…and they kinda, the more and more they would like, forfeit and see the other side of things,

they'd have actually of course see the benefit, but as long as they saw the benefit, they'd kinda join, not the other side, but you know, another goal. And they'd figure that they would be productive working toward that goal and they would, uh, they would all somehow give up and work towards it. It was kind of a game of compromise. But, at the same time, as long as you feel like you can be, you don't think it's like stupid and absolutely not gonna work, like, it always worked out pretty well.

Elliot: I kinda knew that they were gonna choose my house, in fact, I was really betting on it. Because I knew what everyone else was doing with their box houses. And, they uh, like they—I felt like my group was kinda just doing it to get it done. And, it was the simplest way to go about it. So even though mine was like, more complicated, like, they picked my house because it looked prettier than actually, like when we were doing our decision matrix that we had to do for the project, we, uh, like we altered the decision matrix, the weights and everything like that so my house would win because it was more complex and everything like that. So we actually altered it so, like as far as with our criteria, so my house would actually win. Because based on the complexity and everything of the house, it actually lost to one of theirs even though they wanted to go with mine. So I mean, they wanted it enough to where they actually, uh, we altered the criteria so we…even…and then we could say oh we chose this one based on popular opinion. It kinda felt nice, but I kinda saw it coming. I'd be really disappointed if it didn't. be like, really? I wouldn't want to live in that box! [laughs] It's like a prison.

Robert: We first came up with a brainstorming plan, um, and everybody would shout out ideas, no matter how crazy they were. If you attempt to come up with a direction to get started in…then we would all take a vote on which direction we thought was the best to go, and from there, we divvied up who's going to be the time keeper, who's going to be the recorder, who's going to be the coordinator,

> and then we were able to elaborate on the ideas we came up with and weigh the pros and cons of each and determine the best way we could think to go.

The experiences of this category also commented on communicating with the whole team in order to keep everyone updated and on the same page. This is a way that they are experiencing MSPs as needing a continuous negotiation and organization of the multiple perspectives within the team in order to make progress and reach an end goal.

> Neil: I guess just being on the same page with the group, since it is a group project we are working on it together, it is important everyone is up to date on the problem or our solution, I guess…. Because everyone is responsible for the final product, so if we're on different planets in regard to the problem, it's likely we won't like, have a continuous final product that has all of our signature on it.

> Robert: I was in charge of making sure everybody stayed on track and was doing what they were supposed to be doing to get the project done. I oversaw everybody's work to make sure no one was getting confused and everybody knew what the grading requirements were and if we were meeting all those different criteria.

Another salient characteristic of this category of experiences is demonstrated by Neil, who talks at length about the need to organize and motivate within a team so that having multiple perspectives doesn't hold the team back from making progress on their design project. Elliot also expresses the need to "deal with" differences and how the multiple perspectives within a group cause stress for him. Rather than helping the team, the multiple perspectives are viewed as something that is problematic.

> Neil: And we could just sit and talk all day and never get anything done. But at some point, you have to start making progress or else, you know. I wanted to get it done as fast as possible, so I think that's why it's important. … I think, I've experienced this a lot when trying to solve problems – you can like talk forever,

> and just like, talk. But at some point you've gotta like, put it to work. Start putting things on paper and like formulating something. Whether talking for two more hours would get a better solution or not, at some point you have to get going. So having someone to initiate that, I think is important. And yeah, a lot of things I've worked on, have been like just talking and talking. And I want someone to step forward and make it start happening, rather than just continue to talk. … I always try to be, like, practical and keep it…the big thing about how I approach problems is how we talked about how people like to talk a lot and, like, I'm pretty big on getting that moving. I don't really know why, I just have been in a lot of situations where people just talked forever and nothing ever comes from it, so it's important to me to nip that in the bud and start putting pen to paper as soon as possible and making these words actually mean something.

> Elliot: So I mean, it's helped me in dealing with strangers and remaining calm in stressful situations. So if a team member's being difficult, I'm able to be patient with them and everything like that. And uh, yeah, it's just helped me in dealing with people. Because I know people can be, like I don't think all people are bad, but I know like, what, how people can be. … that's helped me as far as dealing with my engineering groups because I'm able to stay patient, stay calm and I'm able to keep myself collected during stressful times at school.

The emphasis of organization in the form of communication throughout the process was also evident within the transcripts that informed this category. Robert describes his role of using communication within his ENGR 131 team to make sure that everyone knew what he or she should be doing in the process of achieving the established team goal. Anne echoes this experience describing her responsibilities as robotics team lead to continue to keep all her team members in the loop with regard to the design so that people remain focus and motivated.

> Robert: It was a lot of communicating between people inside and outside of class and meetings to make sure that everybody knew what their individual parts were.

> I was doing a lot of file attachments between emails, and making sure that everybody had what they needed. I met with a lot of members, more individually to make sure that their work was up to the standards that we wanted as a group. And inside of meetings, making sure that we were all getting our turns to talk and voice our opinions. … we needed to spend as little time on this as possible and maximize the time that we did spend on it to get the best quality work we could.

> Anne: So for this specific problem that I've been talking about, that's a larger team and so we want to keep it as simple as possible to make sure everybody can be on track and be working and progressing instead of everybody getting confused and then we have a communication breakdown and then there's a whole lot of other things that, you know, will go wrong. … Um, when people are following the design, or following the solution that we are currently working on, to make sure they are, they understand the progress that's happening and what the end goal is currently at. So they don't get confused, maybe with what's going on, and then getting discouraged, and then dropping interest, and then you have a bigger break in communication because the interest has dropped and you don't have people working towards a common goal, um, that's another thing, is like when you make a system and not everyone is working towards one point, you're just gonna, you're gonna miss the point, almost indefinitely.

While this category does focus on completing the task, it is qualitatively different than the previous categories as there is an understanding of where the multiple perspectives come from and that there is a responsibility to manage them. For example, Anne reflects on how her role of organizing the multiple perspectives within a design team have realized her interest in pursuing management or higher level organization, such as systems thinking.

> Anne: Um, probably how I, like having a management role in things and how I like looking at the picture bigger, like systems engineering and kinda that bigger picture of everything. Um, because that's just allowing me to see a lot of

> different perspectives, a lot of different people, a lot of how different people think and how different sub-systems need to find their own solutions and how it'll all come together, and how communication affects it especially…in a team setting.

The next category crosses a major threshold from trying to resolve differences into utilizing those differences to generate a successful design.

4.3.5 Category 5 Collaboration (Bentley, Fran, Geoff, Larry, Zixi)

A summary of this category is that engaging with MSPs allows you to utilize the multiple perspectives to defining a problem and designing a solution for that problem. As a team, you can share your perspectives and determine the best idea or combination of ideas to form a solution, which differs from the focus of the previous category on identifying a goal as soon as possible and the coordinating work towards that goal. As a designer, you need to make an effort to listen and consider the ideas of others, who may be right despite their difference from you. This way of experiencing crosses a threshold to valuing the perspectives of others, as they can be valuable to optimizing your design.

This category was comprised of the most number of descriptions of experiences, including five of the 27 total participants. Bentley starts out by describing the importance of making your teammates feel comfortable in order to get them to share their perspective. For him, it is important to get the multiple perspectives voiced, as they are valuable to the process and design.

> Bentley: So usually for me, it's I sit down and half of the time that I've been put with a team, and this is in and out of engineering, it's either nobody talks at all and I've got to be the guy that's like "so what's your name?" you know. "Where are you from?" you know, "what's your experience? Why are you here?" And you just ask the people, get them talking, get them comfortable. … You just get them talking, get them going, make sure you know each other, and then after they're comfortable talking to you and you're comfortable talking back, and then we can start with the engineering. … You don't know who they are, how they are,

> whether they're shy or not, you know. Just like there's confident engineers, there's shy engineers. And you don't want to step on their toes. You don't want to give them this bad taste in their mouth of "oh all of these other people know so much more than I do." When they may or may not, it might just be speaking their mind. And you kind of what to go easy at the beginning, let everybody share their own ideas, let everybody get comfortable; let everybody know everybody, before you could potentially hurt somebody's feelings. So it's always good to go easy at first, test the water, make sure everybody feels like they're a part of a full team, and then you can start developing on the next stage of the relationship that the team's in.

Additional evidence for this category of description of experience includes the emphasis on not only conveying your own idea, but also on understanding the ideas of others, which may be better and should be considered in an effort to optimize the team's design. The way that participants describe their contributions to this category also highlight their awareness of the potential to combine and merge ideas to generate a better solution as a result of collaborating with others with multiple perspectives. In other words, multiple perspectives are productive to the process off engaging with MSPs. These perspectives convey the value of engaging with and combining aspects of multiple perspectives rather than trying to quickly establish a common goal and then moving forward as in the previous category. Engaging with MSPs does not require simply identifying the best possible idea from within the group, but rather the experience expands the design possibilities beyond an individual idea to the additional angles and ideas that other people have beyond the capabilities of a single individual, which leads to a more complete solution.

Fran shares her perspective that engaging with MSPs requires you to speak up for your own ideas and also to seek ways of incorporating your own good ideas along with the good ideas with your teammates in order to produce a solution. Larry shares a similar perspective that the combination of the multiple perspectives within a design team are necessary in order to generate a more well-rounded and complete solution.

Fran: And like on a team, if you're not willing to speak up and have confidence in like, your opinions, or like even other people's opinions, like, that's very hard to work as a team, or get your opinions across, or like, communicate to other people. You know, you're like, well, this is what we're doing, but if you have a different idea, like, we'll change our project, you know. Like, being able to think for yourself and, like, come up—because maybe like, that person that you're talking to does have a good idea, but maybe yours is the better solution for like, what you're working on. And if you don't have the confidence to be like, you know what, like, our project, like does this, and it's also great for this reason, and you know what, like maybe we can work together on this even, like if we want to incorporate both. Just being able to communicate for and advocate for yourself and your project. You know, like, the way you think something should be done. Not like overly pushing it, but like, just like, yeah, being able to stand up for it.

Larry: So…I mean in my team, there's already a lot of disagreement as to what we're supposed to do, so, some, like me I'll say we'll just look off the things we've seen in the past like let's build, let's put like erosion mats and drainage ditches, and others are coming up with, rather, let's make it look pretty, let's come up with something- mixing cornstalks into the ground and just coming up with interesting solutions like that. So it's- a lot of the time everyone has the same goal, but just the means to implementing is different. … The reason in engineering that they have you work in teams is because, I mean, you can't most of the time if you come up with an idea yourself you're not gonna see all the angles to it, all the potential issues. … So now that- that helped with both of our perspectives of trying to come- come up with a better idea. If we're all looking at it we can all identify- everyone can identify the strengths and weaknesses of each person's idea, that can form a much more well-rounded group and decision. … So, the more, the more eyes you have looking at it, the more brains you have

> thinking about it, the more…of all the, the potential issues all the strengths and weaknesses, the more you're going to cover.

Bentley, Zixi and Larry comment specifically on how the differences that stem from engaging with people from different places, different cultures, and different disciplinary training are an asset to the design process.

> Bentley: So by having a team with a diverse background you get ideas and concepts from all over the place instead of just having a bunch of Indianapolis farm kids sitting around and thinking the same thing.
>
> Zixi: Um, I think everybody has a different perspective to a problem. They see the problem differently and everybody is coming from different background, from different culture. And I think everybody here at Purdue is really smart, especially students who are engineering, so I think…it is always good to hear everybody's opinions at times. You don't even think about something and the other guy says it, and then you're like, wow, oh my, why couldn't I think of it? It's really good.
>
> Larry: If you get a bunch of civil engineers and put them together you're probably going to get a lot more homogeneity in your ideas. Likewise, if you've got a bunch of environmental engine- or environmental science majors together, you're gonna get something different but they're all gonna generally think along the same lines. So if you have the differences of opinion, that's healthy because then the different ideas can mix together and counterbalance each other. … And, and then so it's, we have to- when in reality it probably won't, so you have to mix…when you have the different goals together then when you have the different groups, like, okay we're going to make a compromise- sure, we'll do this part this way, we'll do it this way, we'll combine the two. And that, depending on how it's implemented can make the most effective solution. Though sometimes if you can't get to agree on anything, then it can just make you- neither of you will agree and nothing gets done.

Geoff specifically comments on how the diversity within teams is crucial order to generate different viewpoints, which are crucial for navigating the ambiguity of MSPs.

> Geoff: Because if you don't consider everything, then your end solution is going to be biased in some way or another. You're going to be taking into account some things more than other things, you may have forgotten something along the way that drastically changes, or you may have even just forgotten a small thing, something very small that affects one constraint that, well, my whole design revolves around this being possible or this not being possible and now I need to change my whole design. … Really rely on people's backgrounds. And the diversity in our teams, I've found more than once I'll be thinking about a solution one way and then somebody will say something and it'll just spark a completely different viewpoint in my head and then all the sudden, oh my gosh! We weren't even considering this, or this solution. So one way to cope is definitely work with the diversity, work with the different ways of thinking about things in general that we all have. That's definitely one way to cope with it. [sighs] I'm not sure if there really, I mean there's just a lot of relying on teamwork at this point. Now that I think about it more and more, it is teamwork that is definitely one of the most important parts of this. Because I've been helped and then I've been in that position where I've said something and then somebody else was like, oh I wasn't even thinking about that, wow, that's a phenomenal idea or vice versa.

Finally, the participants' experiences that contributed to this category of collaborating through utilizing multiple perspectives describe coming to appreciate the presence of multiple perspectives. This includes willingness to put in effort to understand where someone else is coming and acknowledge their perspective even if it is different than your own. The differences between people grow into something that is appreciated and leads to more productive work and effective solutions. Peers are regarded as sources of knowledge. Fran describes her own willingness to accept the perspective of others and remain flexible when considering that she may not always be right.

> Fran: we don't usually like, have any conflicts or anything because we're willing to like, accept that like, maybe I'm not right this time, you know, like, maybe I am right sometimes, maybe I'm not right sometimes, maybe someone else has a better idea of how to do something. So I think that flexibility has helped. And just being like, you know what, like yeah, no, that's a great idea. I didn't come up with it, but yeah! That is a good idea--we should do that. You know? So. I think that helps.

Zixi describes his own desire to understand the thinking and rationale of his teammates so that he can come to understand their perspective on the design task of improving health on a college campus. He links those individual perspectives to the need to clearly define problems.

> Zixi: But, we, uh we had no idea how he's gonna…what kind of definition does he have in his mind before he came up with this idea? The health. And, how does, I mean before you come up with a solution you need to know, okay, this is the problem and this guy, he's, I mean, okay, if you don't ask me a question and I start answering you without a question, that would be a little, I mean, you would be, okay…what is he trying to say? What did I ask him, I mean I don't even know, okay. And by, maybe, like, after 10 minutes or so you would be like, oh, ooooh, so your point is that you're trying to say this. So we didn't have context there. Okay, this is how he defines the health, and this is why he is coming up with this idea. This is why he…so we need to have pre-context of, I mean, a solution, a problem, which is a problem. Context to a solution is a problem. So we…and the definition of the problem. A clear context.

Finally, Geoff comments on how the diversity within his team is not just a novelty, but a way in which their design team productivity has increased.

> Geoff: And then as time is going on, and we're starting to really take solace in the diversity that we have. Because in the beginning it was less of, it was more, oh cool, you're from a different town. Now it's actually an appreciation that we're growing, each, for each other of the different ways that we think about problems. And I can see how they think about problems, and I can utilize that and toss ideas off them, and the productivity is going up over time. So it's only going up at this point, and we're getting to know each other and starting to like each other more and more and work better as a team.

The next category of description includes understanding the multiple perceptions within your team and beyond using those to create a successful design, also describes the importance of developing an argument to defend why your design is optimal.

4.3.6 Category 6 Reasoning (Casey, Pam, Victoria, Yellena)

A summary of this category is that engaging with MSPs means working with multiple perspectives to generate an optimized design. However, unlike Category 5 Collaboration, the result of this process isn't just a final design, but rather a design with accompanying justification. This way of experiencing shifts from accepting ambiguity to embracing ambiguity as a useful part of the problem solving process. By navigating both the ambiguity and the multiple perspectives, the design team can develop reasoning for their decisions. This is necessary to convince others why your solution is better than the other potential solutions and to "sell" or communicate your design to others, including non-technical individuals.

To start, multiple participants described the importance of their experience as collaborating with their team in order to develop not only a design solution, but also evidence for the decisions throughout the design process.

> Casey: Because you can pick your own pathway, that's exciting. You can go a different route based on what you want or what your team wants, so that's exciting, because it's just more tailored to you and what you want to do, what you

think is right. So making it kind of argumentative, you can make it argumentative too. So that's kind of exciting to be like, "okay I designed this, and I made this, and this is how I do it, and I feel like this is the best way to do this because of this. And this worked out because of that," that kind of thing. So that's enjoyable, to know that you could go so many different ways, but you decided to go this way and it was successful. … It feels good, because you obviously, you can say that your solution worked because of those things and because you're basically just making your argument for what you believe in. And what you believe is the right way, or like what worked out for you in your process, so my argument, making an argument and not really arguing, because you're not clashing with someone else mainly. But you're basically presenting, like, "Hey this is my idea. We think that this works better because of…" … Because I mean there could be other teams that went from point A to point D and all the branches in between and didn't think as much about it, but they still got a good solution, but because we're making that argument, we can make that argument, because we know what we did in those steps and we know why we did it. That's rewarding. … If you're working from point A to D, and you have a bunch of different pathways and solutions, why did you pick that way? That's more important than just saying, "hey well we have a solution. Yay." No, there should be hardcore thought processes, hardcore design processes that went on, and you should know exactly what you did and you should have made those decisions because you figured this out or you decided to make this decision based on these factors. If you don't have that, then your design, you don't know really how you got to your design. ... So that's kind of important to me. You should know what you do to get to where you are.

Pam: But yeah, the reasoning, like having a lot—like, they always tell us about, like engineering based decisions, like having a reason why you got to that decision, you know. It's not something you just came up with. And they always tell us this, it's like, especially in engineering there's never one right answer, but if you get to an answer, you have to give them a reason why you got that answer,

> so it's not like, hey you have the right answer, you can do whatever you want. No. you have to get the answer and explain the answer, you have to explain the answer. So that's the whole thing.

> Yellena: Problem solving, for me, is that start to finish process. It's not just being able to define a problem and say, "here's 5 possible solutions." It's being able to say, "Here's my problem, here's research saying there's a problem, here's studies and surveys saying there's a problem. Here's other patents showing that people have tried to fix this problem. Now here's some sketches. Here are where I'm going to get the materials I need, here's the cost of what I need. Here are the facilities I need. Here's how long it's going to take. Here's how I'm going to distribute it, how I'm going to market it. How I'm going to sell it to companies." Like, problem solving is that beginning to end aspect. It's not simply just thinking of an idea that could possibly solve our problem. It's being able to justify it, start to finish. … Like your solution is obviously the biggest deal, but how you support your solution is almost just as big of a deal.

This category as a way of experiencing problems with multiple possible solutions also was developed based on descriptions of using persuasion as a way of establishing that your idea is valid. Victoria describes how her experience on an EPICS design team included awareness that solutions are evaluated by convincing others that the solution is good.

> Victoria: Um, since it's got multiple solutions, um, and you could think of it any way, for your answer to be, I guess, kind of "right" in the general scheme, you have to have multiple people that back you up, or your answers never...even if there's multiple answers and you technically can never be right, like, you are not on the right track, unless you have multiple...like you can't be the only one who is like "oh, yeah this is a good idea". That's not going to get you anywhere, if you're the only one who thinks it's a good idea.

Later in her interview, she reflects on a high school science project where the reason she did well was not because her solution was the only possible solution, but rather because she could justify her decisions and persuade others by using that justification.

> Victoria: And I never thought that the project itself was very impressive but clearly, apparently, the way that I said it, like, it worked. So, it feels the same way with things that have multiple solutions. You could technically...like, if you convince the person, if you persuade them that, yeah your answer is the best answer...even if it doesn't solve everything, because you've talked your way into it.

Finally, the use of reasoning to justify your design is also described as being important in order to communicate to others outside the design team. This may include convincing someone to invest in your solution or trust you in the workplace. Pam emphasizes the need to work through ambiguity in order to develop the ability to communicate your solution to others outside the design team. Yellena shares a similar perspective that within the workplace it will be necessary to provide sound evidence for your design decisions.

> Pam: And it's not only knowing how to solve a problem, but knowing how to solve it and explain it to people. Explain to people that don't really know what you're talking about, but you have to be able to communicate. Because the two things they'll ask you to do in engineering is solve a problem and explain it or try to sell it or try to, you know, tell people how you did it. So communication, and…problem solving.

> Yellena: Because once you are working in a real job, you're not going to be able to sell your idea like, "hey I thought of these ideas, this one turned out the best, you should support me in it." No one's gonna believe you. You have to have the research and the evidence and the justification to convince them that, "yes, this is why this is the best solution to this problem."

The ninth and final category moves into utilizing multiple perspectives for the sake of developing a design and evidence for design decisions to internalizing these perspectives for personal growth towards becoming an engineer, or person who engages with problems with multiple possible solutions.

4.3.7 Category 7 Growth (Matt, Quinn, Shaun)

A summary of this category is that Engaging with MSPs and their ambiguity is valuable because the experience exposes you to multiple perspectives, which not only improves your design, but also expands your own thinking. You learn from your team through internalizing your understanding of their varying perspectives, and that understanding stays with you after the design is completed. MSPs are an opportunity for personal growth in becoming an engineer.

To start, each of the transcripts contain evidence of the participants describing their experience as an opportunity for them to not only understand the multiple perspectives of others, but also to internalize those perspectives and change their own ways of thinking.

> Matt: When I interact with the other group members, and like I said there is a lot of diversity within our team. So, when there is a lot of diversity within our team we, like I said, then we approach, like, Chinese approach problems differently. The person from Thailand approaches problems differently. I approach problems differently. Then there's the guy from US who approaches problems very differently from us. Like, we three, we are all from Asian countries and our problems, like, the way we approach still it's different, but it's sort of related. But the way he does it, he does it completely differently. So, now, when we come up with, like, different solutions, like I said, it's sort of a problem. But, like, obviously when there are multi solutions to it, you obviously learn a lot. Like, okay, I thought this way, I thought in this direction, I could've gone that way too. So when you think, like, okay I could've gone that way

too. Like, the way you think about it, when you go in that direction you're gonna come up with a new idea. So that is how I think that it helps you broaden the way you think, this class. Taking different sides to how you think.

Quinn: But that, the criticism, no matter the importance of the project or whatever you are working on, shouldn't affect how the criticism is taken. So you should always think of it in, you should always take away something from the criticism and be, like, this person caught this for a reason and I know I didn't see it, but they saw it and that should mean something to you –that maybe it wasn't the best idea, but they still were able to and you have to rethink what they pointed out. I guess. Um. I don't know how else to word that. Because you always, they'll catch it and then you have to think about it, even if it's not a good idea, you'll still think about it and reform thoughts and reconsider it.

Shaun: In engineering you take what you've learned to kind of broaden your mind and open it up so that you can kind of look at many different solutions. You can solve a problem in many different ways to get many different solutions rather than solving it one way and getting one solution. … And when I got to engineering, thinking that I know it all in, whatever, like, thinking that I know the best way to solve this solution is really like, and like, knowing now that I'm not and that other people have so many great ideas kind of has changed how I view that, and like my comfort. Because now I'm really comfortable working with people and now I'm really comfortable asking other people what they think of a problem, or how they would solve it, how they would approach it. So, yeah.

The experiences that comprise this category also demonstrate the perspective of these students that their peers are valuable sources of knowledge. Quinn describes her perspective related to working with her EPICS design team to develop an education website. Her perspective emphasizes her openness to learn from her teammates, who are committed unlike her previous experiences in high school. She also comments on internalizing the feedback from others and states that it is only through help from your peers that you can succeed.

> Quinn: Um, with the team, um, listen to your teammates. Don’t shoot down anything right away. Know that [pause] their answer, unless it’s completely ridiculous, is not wrong. You have to keep that in mind, that your solution mind is not necessarily the only right one, that they could also be right and you have to be able to accept that and step outside of the – it’s not a bad thing to have that, like, conceited mindset, but it’s still, you have to be able to take – like step in the shoes of someone else and see their point of view and it causes you to look in a lot of different directions. … I know in high school, everybody, one person ends up in charge and they have to, like, do the project all by themselves. You get this bad idea of a team, and you’re thinking, wow, I’m the only one that knows how to do anything because in high school I was the only one that ever did the project, and everybody else slacked and did nothing and I was stuck with all the work. Whereas, here, now I’m surrounded by people with similar aspirations as mine, in regards to engineering at least. So I know that they, like, they want to figure out the problem as well, but they also, and like, trust your team, and what they’re thinking and what they’re saying is a possibility to finding the solution. ... So, um, I guess with your project, you think about the project and think oh this totally makes sense and I could totally see how it works and all these different aspects, but when a TA or another team member is like now take a step back and see, here is a flaw in your project and then you’ll remember that flaw and be, like, in the future if you have to make another project, you can, I guess remember what they said and also remember to not be afraid to get feedback, that criticism extremely helpful and I guess good criticism is helpful. It just helps you see your project in a new way and develop it to become stronger because, uh, like nobody can get to the top without any help from somebody else, your peers are, like, I guess, an extremely important aspect to success. In the idea of multiple solutions, teams are important. I guess that’s probably the most important thing to me, is that you

should definitely…advice from your peers is probably your greatest, is the greatest thing that's gonna help you.

Shaun describes the change in his perception of problem solving after experiencing the design task in ENGR 131 to improve health on campus. He emphasizes that through engaging with multiple perspectives, he not only saw the problem from a different perspective, but also reflected on that to inform his future problem solving approach.

> Shaun: So, I don't know, going back to this design problem. I didn't really see how having extra counselors on campus or in extra buildings would really affect it because I didn't really think that people would need that. But I think that the fact that if they were there and easily accessible like anywhere on campus other than like, making an appointment at PUSH or something, um, I saw how just having those people there would really help people with dealing with things such as like, a hard test or something, like, just having them all over would really affect people in a positive way, I think. So that's something I didn't see before but with talking to my other group member it kind of showed me that. … Um, having the ability to converse with your group members and talk it over and understand where they're coming from is really important when you're trying to solve these problems.

And finally, these experiences include a future-looking perspective on how these experiences with MSPs have changed their thinking in a way that will be maintained beyond the immediate context. Quinn and Shaun both comment on the way their experience with MSPs has changed their thinking and caused personal growth.

> Quinn: Now I know to listen to my teammates. Um, and that, um, I've since learned that even if I have an idea in mind, and am like this has to be right, I know this is right, this is how we should do it, somebody else may have the same thoughts and if you can mix them together maybe the two thoughts could form something even better than both of your ideas alone. Or you can combine them to

> create, like, double awesome project! [laugh] And so, I guess it has changed my thoughts on how to perceive a team.
>
> Shaun: So, the fact that people had other views of the problem and different solutions that also worked very well kind of changed my perspective. It kind of opens my eyes to see that there are so many different problems that can—or so many different solutions that can be used to solve the problem. … I used to have really bad tunnel vision. I was focused on, like, one thing all the time. If a problem was given to me, I found a solution really quick and then wrote that. So, I didn't really open up my options ever. And now I'm coming into this class, um, changing my perception on how a problem can be implemented, or how a solution can be implemented. Um, seeing all the different options really has just allowed me, now when I'm solving a problem to consider everything. And, it's really helped me with that so that I can solve it better rather than just trying to find one solution quick and taking that all the way, I guess.

This section has presented the seven qualitatively different ways that first-year engineering students experienced engaging with problems with multiple possible solutions. Including: completion, transition, iteration, organization, collaboration, reasoning, and growth. Excerpts have been provided as examples of the evidence for the development of these categories. They have been presented in order of less to more comprehensive, and the rational for that hierarchy is detailed in the next section.

4.4 Category Differences and Resulting Hierarchy

As presented in the analysis section, the transcript data was used to iteratively develop qualitatively different categories of experiencing problems with multiple possible solutions. These categories represent the most complete way I found of capturing the key aspects of the way the participants describe their experiences from their own perspectives. However, many of the participants provided small amounts of insight into other categories, which helped to build the logical relationship between the categories. Throughout the process of developing the categories, I noted instances of participants conveying an awareness of categories beyond where they were categorized, and that awareness helped me to establish the relationship between the categories. This is in accordance with the method of establishing a hierarchical outcome space through demonstrating inclusion of less comprehensive categories within more comprehensive categories. As Åkerlind, Bowden and Green (2005, p. 95) explain, "the hierarchy is not one based on value judgments of better and worse ways of understanding, but on evidence of some categories being inclusive of others."

In alignment with the theoretical framework of phenomenography, these categories and this outcome space were not developed with an intention to identify individual students or label any student's experience as better or worse than another, only has more or less comprehensive. The data only conveys a snapshot of fragment of the awareness of the participants, so in another situation they may demonstrate characteristics of a different category than where my analysis of their single transcript categorized them. In addition, the axes of variation were identified as ways of understanding *all* the transcripts in the data pool, so other ways in which transcripts varied were considered noise. This inherently loses some of the nuances of the data as the individuals are not fully captured by the category the contribute to or their place in the resulting hierarchy (Barnacle, 2005; Cherry, 2005; Åkerlind, Bowden, & Green, 2005). However, these findings are in alignment with the motivation of phenomenography to "describe variation in experience in a way that is useful and meaningful, providing insight into what would be required for individuals to move from less powerful to more powerful ways of understanding a phenomenon" (Åkerlind, 2005a, p. 62).

The next six sections present overall descriptions of the qualitative differences between the categories that include more nuances I gained from my familiarity with the data that are not captured by the excerpts presented in the descriptions above.

4.4.1 Transition from Category 1 to Category 2

Category 1 is the least comprehensive of all the ways of experiencing problems with multiple possible solutions. Students are focused on finding information that will allow them to treat the problem as though it is well-structured and quickly finish the task. The transition to Category 2 includes reflection on the purpose of engaging with an MSP. Students are still oriented towards the classroom requirements, but they seem to have a different perception of what engineering is. They acknowledge that engineering work requires the navigation of ambiguity, and while they don't try to eliminate it, they describe the difficult of transitioning to a new "mindset," which requires working more independently. This transition also includes a shift from viewing the experience as unimportant to a view that learning to engage with MSPs is a necessary part of preparing for a future job as an engineer.

4.4.2 Transition from Category 2 to Category 3

The transition from Category 2 to Category 3 includes an acceptance of the ambiguity inherent to ill-structured, open-ended design tasks. Students shift from a focus on meeting course requirements and their own learning to displaying autonomy for contributing to the problem and fixing or iterating to improve the existing design. It is as though they accept the challenge and are the first of the three categories that are focused on the output of the design process and generating a successful design. Category 3 is the last category where the idea of multiple perspectives is primarily focused on seeking an outside perspective that holds truth and can inform the behavior of the problem solving team.

Excerpts from transcripts in Category 3 demonstrate some evidence for why it is considered more comprehensive than Categories 1 and 2. Participants do exhibit an awareness of the key elements of the less comprehensive ways of experiencing MSPs. For example, Xin describes seeking feedback from the instructor to be sure to complete the requirements within the classroom context.

> Xin: So the instructor I had, he was kind of, he was kind of goofy in his own way, but um if we had a question about the project, what requirements we needed or like maybe advice on how to go about building something, we'd ask him and he

> would usually help us out. … Umm, so we did kinda need to get feedback from TAs, professors, make sure our like, process was uhh, in the right direction, made sure that our pieces were up to par. Make sure we understood, like, what we actually needed for a project.

Karl also demonstrates that that the previous focus of understanding the course requirements and seeking information to ensure meeting those requirements is also a part of his experience, even though his overall experience is more focused on iterating to improve a design. Grades continue to be a consideration, but they are no longer the most salient aspect of the experience as they were for Categories 1 and 2.

> Karl: Um, I think it's important to interpret it clearly just because since there are so many, since it's such a, such like a wide range of correct answers, or correct solutions for this problem that you can interpret it incorrectly and still think that you're doing it correctly just because it's just so abstract in nature. And, in which case, you just fail the project and the whole class would suck a lot. … Uh, well, for me, I went and talked to our GTA and made sure, I was like hey, uh, if we do this, would this be alright? Is this gonna make sense? Would this meet the criteria set on us? And he was like yeah, that's fine. But, um, if I did not have access to a GTA, I don't know. I don't know how I would've done it. I think I would've just kind of gone with my gut a little bit on it. … I don't know how I would've approached this problem if, like, if they had said this was not related to your grade, I don't know how I would've approached this problem. I don't think I would've done this solution—I might've tried to do something a little bit more difficult. Um, I chose, one of the reasons why I chose this is because I know, I know how to code this solution. So, even if my teammates decide not to do anything, I know I can get this done, and I know I can, like, still pass this class. Um, if this was not dependent, if my grade was not dependent on this, then I would maybe have chosen something a lot more difficult.

Oliver also mentioned his awareness of the transition from engaging with SSPs to MSPs, which was critical for the transcripts that informed Category 2.

> Oliver: If I didn't, I think I'd give up a lot, if I didn't have any of those experiences, if I just came to…I had a lot of problem solving stuff in high school so if I came to college without any of that and just came into engineering class, I'd probably hate it, just absolutely hate it because I wouldn't know how to think that way because it'd always be, oh I'm used to this one answer, let's just get it and be done with it instead of trying to think of multiple solutions and which one's the best for everybody or specific audience. I think it'd be a lot tougher if I don't have those, or if I run into something later down the road that doesn't have a right answer. I'm always used to having a right answer so this is definitely helpful in that sense. … I know what I'm going to do to get to the final answer even if it's hard, whereas if I didn't have any of these, I'd come across something and I'd have no clue what to do, and I'd probably just continually, like, hit a wall and not know how to get around it because I wouldn't know how to problem solve or think of multiple solutions. I'd just be trying to get to one solution, even thought that solution might not even be there.

4.4.3 Differences in Category 3 and Category 4

Category 4 differs from the previous categories as students now describe the role of multiple perspectives as a function of the diversity within their own team. These differing perspectives generate the need to systematically organize the different ideas within the team into a common vision that everyone agrees on. This needs to be done so that the multiple perspectives does not hinder the team from progressing towards achieving a design solution. Students are still accepting of ambiguity, but they do not focus on seeking out external examples or opinions as a way of coping with that ambiguity. Instead, they identify ways of conveying information within their team and then resolving the differences to a consensus.

Category 4 can be considered more comprehensive than the previous categories as many aspects of those less comprehensive categories are also mentioned in the transcripts that informed Category 4, but not as an essential aspect of their experience with MSPs. Evidence for how these aspects are included within the data includes references to seeking information in order to complete the task or satisfy the course requirements. Elliot, Neil and Robert all acknowledged an awareness of a need to complete the requirements for the course.

> Elliot: But, it was uh, it wasn't very difficult in the class to keep everything going in the right direction and keeping everything, um, going efficiently. It wasn't really difficult to keep anyone on task, or anything like that because we all knew the due date and we all knew what we needed to do. So if we saw the amount of work that we had to do was a lot, then we wouldn't mess around. Like, it was self-governing, like everyone was self-sufficient and working, so we were able to do things rather efficiently. That's why I said that there was really no set leadership in the groups because everyone was really able to work efficiently, parallel to each other.

> Neil: Well, because, well there is a due date. And we could just sit and talk all day and never get anything done. But at some point, you have to start making progress or else, you know. I wanted to get it done as fast as possible, so I think that's why it's important.

> Robert: We have a limited amount of time to come up with our final solution, and if we get off track then we're wasting time and most of us are very busy outside of our various activities and what-not. So, we needed to spend as little time on this as possible and maximize the time that we did spend on it to get the best quality work we could. … If you don't know what you're being asked to do, there's no way you can do it. So knowing who's going to do what, how they're going to do it, what each person's responsible for, you're able to bring everything

> together and to actually solve whatever problem you're given or complete whatever assignment you have.

While Category 4 goes beyond seeking the information of outside sources to acknowledging the need to coordinate multiple perspectives within the group, information gathering is still a part of their experience. This includes seeking more factual information about the context and constraints of the problem as well as the opinions and expectations of their instructors.

> Elliot: Usually we started out with codes, figuring out what we could actually do. As far as like, building heights, and how much, um, like the location, whether the runoff will go into a river, or, where it'll go. Stuff like that.
> Robert: We looked at the, uh, kind of pseudo-rubric that they gave us for what they were looking for, and then we discussed as a group…okay, that's what they're looking for. How do we envision that looking? Okay, that's what it needs to look like. … A lot of times, when we would ask a peer teaching assistant, they would try to help us and then send us to graduate teaching assistant who would be grading it because they weren't sure what he would be looking for since there really was no grading rubric for them to look at, and occasionally even we would ask the professor, she would still have the graduate teaching assistant look at our work because she doesn't grade it either. … If they have a more concrete rubric or outline of what they were looking for and what gets what points and how much it's worth, that every member of the instructional team would be able to see, it would be a lot more helpful for one of the peer teachers to come over to a group and be able to answer a question much quicker than having to wait for the graduate teaching assistant to make his way around to every single group.
> Elliot: Their input, like if you could, if you have an idea that comes to mind, then you could talk to them about the idea and get their opinion on it. And, uh, if they think it's a good idea, then you can go ahead and pursue it, but if they—if they think it's a bad idea, you can either alter it, or you can just trash it all together. So

> I mean that's, like I would ask [faculty name] if an idea was a good idea. Like whenever she comes around and asks how we're doing, and everything like that, and tell her the ideas that we have at the moment. And, um, based on how she perceived them when I said them, kind of tell which ones were pretty good or which ones were pretty bad. And she would say a few things on them, and that would kind of nudge us in a certain direction.

Finally, Neil also includes evidence of his awareness of his own learning that is, in part, a transition towards becoming better at engaging with different types of problems.

> Neil: Every time I work on one, it's, like, adding a new twist to how I solve problems, like, because I definitely pull from past experiences when I solve problems. So, like, approaching every problem, well every problem has a different approach, I would say. So adding different approaches makes me more open minded about how to solve a problem and then also, just better equipped to solve a problem.

4.4.4 Transition from Category 4 to Category 5

The qualitatively different ways of experiencing MSPs in Category 4 and Category 5 represent a major transition in the way students describe the role of multiple perspectives. This was identified as a major threshold for the experience of engaging with problems with multiple possible solutions and is discussed further in Chapter 5. While Category 4 is about organizing and dealing with differences, Category 5 shifts in to valuing the multiple perspectives of others within the design team. This is a major shift as students now find it important to solicit the views of others as those views may be better and can contribute to the overall design. Students see value in the time spent understanding the views of others as well as utilizing those views to generate a design that is more well-rounded and less likely to fail since it is the result of multiple viewpoints and ways of thinking.

The transcripts that contributed to Category 5 talk explicitly about an awareness that their experience is about more than completing the task and earning a grade. Fran describes how she is motivated by grades, but she also describes a sense of autonomy to engage with the process in a way that is interesting and facilitates learning for her.

> Fran: I mean, like, obviously its school and good grades are important to me. So that is motivating. But honestly, like too, as you get more into the project, coming up with ideas is always fun for me and seeing like, new things you can come up with. So kind of like that challenge aspect of it, like, okay well, maybe it's not interesting, but what can I come up with that would make it more interesting, I guess. And if that's something that's like not extremely and won't pass the first round of ideas, but just like, coming up with different things that you can possibly do makes it more fun. … I like get very bored when I'm not being challenged, which I think is kind of what drew me to engineering. Because I always felt like I was always doing something. And even like, in a career, I felt like I wouldn't be doing the same thing for like, 50 years without having any change. I like things more dynamic, not static. So I like that you're always like learning, and like, new things are coming up and you can add to that.

Larry describes his experience as a part of an EPICS team looking at the erosion in Happy Hollow as distinctly different than coursework that is just for a grade. He emphasizes his increased investment in such a real-world problem.

> Larry: You're, that one is a textbook problem you're just doing it to master the material. That one wasn't particularly difficult, it took maybe 5 to 10 minutes to get it done depending on how many mistakes you make. So, in that one if you, and if you do it wrong, you just get the problem wrong and have to do it over. Uh, now, the park, that's different. That problem wasn't, that one was formed on its own, it's a real world problem. Real world problems have a lot of different…have some givens and unknowns just like a math problem in a textbook, but the

> numbers aren't so clean cut so that they'll come up and give you a nice well-rounded answer. There, its not a, its not like in the math problem, there's only one way to do it, you apply this one formula and if you do this all, you will get the right answer every time. The park, no one really knows the exact solution to it. It's just a problem that we observed. … Its more, "Okay, so I'm thinking, I'm trying to figure out a way to solve this problem." What are the stakes? Well sure, I have a grade in this class, but that's not the point. It's also the cost, the money is…where is it coming from? Some of it's coming from grants, some of it could be coming from the city, meaning it's coming from taxpayers, so it's, you don't want, you don't want to spend all that money on something that doesn't work. So, you have that at stake. You also just have like, if we don't do anything about it, eventually the park, the erosion is gonna get so bad that it's just gonna kill all the trees. The house at the top will soon could eventually be at risk of sliding down the hill if they don't do anything about it. The river will become much more polluted from all that sediment. There, there are real consequences to not doing it but also to doing it wrong. So it puts a, like there's stakes, the stakes are higher. If you, there's a consequence for if you build it right, there's a positive consequence, if you build it wrong there's a negative consequence, and if you ignore it there's a negative consequence.

In a similar demonstration of experiencing MSPs in a more comprehensive way that the lower categories, Geoff describes his reaction to ambiguity followed by a perspective that it is a good thing for his learning and future.

> Geoff: There has been a lot of…nebulous is a good word to describe it, confusion going on with these problems and interactions, where we'll ask a question, and then the TA will look at it and say, I have no idea, let me go get the graduate TA, and he'll say uh, just ask the professor. And then we ask the professor, and she'll say, oh I don't know and then walks away. And I think that all does go back to making us think for ourselves, which I'm all for, we do need to learn to think as

individuals and not need to be told what to do. … And I think it might be a good thing that it is so nebulous, honestly, it's confusing and frustrating and annoying, but it's a good thing because that is how the real world works and whenever you complain to anybody who's an engineer, or anybody who knows, you're basically told well that's how the real world works, we're not given concise problems, when we need help, we need to figure it out ourselves, we don't have a professor to tell us exactly what the solution is or how to think about it. So I do appreciate that they're starting early trying to get us to think about this differently, and all the people I've talked to have said Purdue engineers think differently, so maybe this is part of the whole process. At this point, I can appreciate that they are giving us room to make our own solutions. And think about things our own way.

This group also includes demonstration of characteristics of Category 4 by acknowledging the aspect of engaging with MSPs that requires the organization of individuals towards a common goal and the arrangement of logistics. Bentley describes the need to learn the strengths and abilities of his teammates so that you can trust them to get work done.

Bentley: So in engineering, say I'm thrown into a team of people with diverse backgrounds. I don't know their story. I don't know them, but, I now know how to work with them so I can maybe learn a little bit about them. I can figure out, you know, who's the mathematician, and who's the best at writing papers, who's good at x, y, and z and orchestrate work appropriately. … So as you become a team, like you said, you get to know the people. It gets more friendly. Assuming you're all mature and good about people making mistakes, you'll get to trust the people a lot more. And say you have that hundred point engineering assignment and you're working with a team you've already been with. I know that he can do this and I'm comfortable giving him this task. So that you sleep easier at night and you probably get a lot more work done too, because you're a lot less hesitant to hand out jobs.

Geoff describes his own experience as including the need to motivate and organize the individuals on his team so that they can progress to a solution. Again, this is inclusive of the previous category, and while he does show his awareness of it, it is not the overall critical way of experiencing MSPs for him.

> Geoff: My role, I have taken a leadership role, for sure. Many a time, we've been sitting there unproductive, and I've had to, alright guys, let's stop what we're doing real quick, let's bring it back, what do we want to do? How do we want to get this done? And that has been, actually extremely effective, because the type of people that they are, that they're fantastic people, but sometimes when they're lacking motivation the productivity comes to a halt and somebody has to do something. And I'm the kind of person that will step up and take that role and really bring people together and then make progress and make goals. … It definitely, well it feels good to be able to communicate well with people and read how people like to be communicated to and how they want to be communicated to. So it definitely feels good, I feel like I'm gaining experience, learning how to talk to different kinds of people, and how to communicate with them. So it's been a good role. It does get stressful at times because I feel like I'm the only person pushing the team forward, it's not that I'm the only one doing the work, because that's not a problem, anyone that comes here is willing to do the work, but it's pushing the team forward and setting goals and making sure everybody's on task, doing the, actually moving forward and making progress. And that's one of the things that I'm good at – is making people move forward and get progress.

Fran goes on to demonstrate a more comprehensive experience of this aspect of working with multiple perspectives by describing the need to remain flexible within a team in order to be supportive and effective.

> Fran: Yeah. I think it's important, um, group experiences…if you have too many type-A people in one group, you tend to get people fighting for like who wants to be like, the leader and decide what people do what. And you just, you can't have too many leaders on a team, you have to have followers at some point. Even if you like, switch roles, I mean, like sharing control of the project and like, tasks. Because maybe someone's really good at coding, but like, you need people who are also good, you know, like not everyone can be good at the same thing or have like, I mean I guess you can all like the same thing as long as you're open to trying different things. So like, that flexibility in like, what you're willing to do and what skills you have or are willing to learn to better support the team.

As a final demonstration of Category 5 being more comprehensive than the previous categories, excerpts do convey an awareness of the transition towards engaging with MSPs that they were able to accept and not have define their experience.

> Fran: Um, I think I've—I mean, well I mean, I've had like a lot base of like, I mean, by the time you get to freshman in college, hopefully you've had a pretty strong base and like, um, educational base and just knowing how to complete assignments and knowing how to do things professionally, I guess. And, I don't know, I'm like the youngest child in my family, so you know, you kind of like see people grow up, and like, it just feels like a very natural process of like, being given more freedom and like, I mean, you come to college and you kind of expect it to be different than high school, you know, you don't want to be doing the same thing. So like, giving that more degree of freedom to like think, I guess wasn't unexpected coming to college.

Bentley even goes as far as to describe his recognition of why the course is structured in such away for allow for individuals to transition if they hadn't already. He also describes his own desire to use even more creativity within his coursework in the future.

> Bentley: And so as we progress through the class, they are getting less and less restrictive. Which I like and which makes sense to me, because there are, going back to the different backgrounds type of thing, there are people in that class that aren't as, you know, maybe they weren't in Project Lead the Way, or something. And so I can understand why they would need to make the class regimented and then expand it out. Maybe not to the extent that they do, but I can see why. And so our most recent project was that. … I'm really looking forward to actually getting in all the classes where I can use creativity to solve my problems, as opposed to "you're gonna do this this way and this is why you're supposed to do it this way."

4.4.5 Differences in Category 5 and Category 6

The shift in way of experiencing MSPs from Category 5 to Category 6 can be described as moving from accepting ambiguity to embracing it. While multiple perspectives are still maintained as a valuable part of effective problems solving, ambiguity is also now viewed as a crucial component. This way of experiencing is no longer about completing the task or design, but goes beyond that goal into generating a design that is accompanied by justification for that design. This includes evidence for how design decisions were made, which is considered an important deliverable along with the final design. It is through embracing the ambiguity and related multiple perspectives that this justification can be generated.

The evidence of Category 6 being categorized as more comprehensive than the previous category includes data referring to completing tasks, the transition from SSPs to MSPs, organizing group members and utilizing multiple perspectives to generate a successful design. To start, while it is the main focus of her experience, Pam does comment on the need to complete the task through organizing within the team and her appreciation of how her team was able to do that well.

Pam: Well, because you don't want to do it all by yourself. It's a lot of work. And they make it, I feel like, especially the modeling and design, they make it in a way that's not easy for only one person to do it. I think it's, if one person was to do everything, it would be just, a lot of time into it. So they make it in a way that you can easily delegate tasks because, they give you, like, check lists. So we can easily say, hey guys, I do the two first ones, you do. So you just break it up, so you can do it in class. … If you just do, if you check all your checklist once, and everyone does their stuff, their part, it's just so much easier. And my group is pretty good at, we've done everything up to this point. And we're always before, I see people, like working the night before, I'm like, yeah, I'm done with that. That was pretty cool.

She goes on to explain how her experience was not really about the actual task (which she didn't like), but rather about the experience of learning to communicate the justification for your design to others after working through the ambiguity and multiple perspectives of the design.

Pam: To be really honest, I don't like the shopping cart thing because I think they could have given us something that's more relevant to our – you know, like some kind of problem that Purdue has, or some kind of problem we have in the dorms, something we can actually, you know, relate to. Shopping carts was really, like, abstract for us. So it's really hard for us to be like, I don't know, when I go to do groceries or whatever…I live in the dorms, so first I have dining courts. Second if I go buy something, I buy like one or two things. I had the one problem where I had the two water bottles – packs, but it's not something that, like, oh my god, I need a shopping cart, you know? It's never a need for us, so I wish they could have given us something that's more relatable, but I like the class in general. It's like, you learn how to like communicate and usually when you go, like, to the real working, field or whatever, you have to explain design processes and all that to people who don't know about engineering. It's like, you have tell, like what if you

> developed a software – you have to tell people who have no idea what you are talking about what the software does. So you have to avoid, all like, the technical language, and be like, hey, it does this. And you have to do make comparisons and all that.

Participants whose description of their experiences contributed to this category also acknowledged their awareness of the transition needed between engaging only with SSPs to working with problem with increased ambiguity. However, this was not the aspect of engaging with MSPs that framed their overall experience. Victoria and Yellena discuss how their previous experiences in high school catalyzed their transition such that it was not imperative to their experience as first-year engineering students.

> Victoria: So, I did it the way we learned in high school, I wrote my code out, and it was frustrating at the end because when you asked around your group, no one had the same thing but we were all coming up with the right answer. And I was so used to in high school they guided us like you put this for your input, you write this exactly, and this is what your output is gonna be. And so I was so used to thinking that this is right and this is what I learned in high school and this is exactly how it should be. And like my group members were like oh, well you could also think of it this way, so at first it was frustrating but as time went on, I just got more used to it. … Um, sometimes it feels like you don't get as, or because like, I guess since it's frustrating for us right now to not get like the answer right away but like they're just trying to help us grow, so sometimes they do just give us the answer right away and it's like 'oh maybe that would have been, more benefitted if he didn't give me the answer right away and just let me figure it out on my own.

> Yellena: Freshman year it was really frustrating, until I kinda realized, okay, like this is what's helping me learn and um, once I got to like senior year, it was more like "ok I going to go and work for the first half hour and the last 5 minutes take it

> up and be like “hey, did I get anywhere in the right direction,” and like looking back, its helped me a lot here in college, even this first semester.

Casey comments on how she has observed the transition as a salient aspect of the experience for others in contrast to her own experience of embracing the freedom to work through the ambiguity of a design task.

> Casey: I think it's challenging for some people. I feel like it's very challenging for some people, because some people are getting frustrated that there's not a right answer. They get frustrated that they don't have as many set deliverables. There's not as much direction and they feel like that's challenging because there's not a real direction. You have to go figure things out on your own with your own thought processes and implementing solutions, evaluating different aspects to them, analyzing multiple things.

Navigating the need to organize and work with others was acknowledge in these transcripts, but it was also conveyed that this process was not a barrier to progress, as it was for the experiences that contributed to Category 4 focused on organization. Victoria describes the benefits of working well with her teammates.

> Victoria: Umm...I guess at that point we were all very comfortable with each other so it just felt like we were just chatting with your group. We just sat around at our table. … Umm like I gave my idea, they nodded, they were clearly listening and afterwards they gave me back the feedback, what they thought. …Completely comfortable, they felt like friends of mine, so… … I feel like you don’t, you’re not as restricted; you don’t feel like you have to hold back your ideas because they won’t accept it. You can be more open and actually say what you’re thinking.

Category 6 can also be considered more comprehensive than the previous category revolving around collaborating with others to develop a design, as that aspect of the experience was also included within the transcripts for this category. For example, Yellena describes the merging of ideas as an aspect of the process that she is aware of.

> Yellena: Umm a lot of our developing for at least our group came from sketching, just pages and pages, we 'd just start drawing and then be like "nope", and we'd just kind of like set it over. Like, we had like two binders just full of like notebook paper, computer paper whatever we felt like using that day. Crayons markers pencils. And we would just sketch and we'd say like "ehh." Like, a lot of our drawings had like sketches or half sketches with circles around different parts, like "I like this aspect, I like this aspect". So like, every couple of days like we'd go through and say, "okay, how can we bring these together?" And we would draw them together and we'd look at it again and like, "ok and we have this with different parts, this I guess isn't so desirable." So then we'd…it was a weird tactic we took like visual, puzzling together type of tactic.

Casey also describes collaborating as a team to determine an optimal solution, and goes beyond recognition of the result being the design to the result of the process also being a justification for that design.

> Casey: We had a little tutorial that was online that we could look at as far as how to work the program, but other than that we didn't get any instruction whatsoever. So we had to work through, we were like looking at the tutorial, figuring out how the program works, and then in my team we, all four of us designed four individual solutions. And then after that we had to collaborate and decide which one of our solutions was the best one. So that left a lot of room, like you could do multiple different things. We saw completely different types of houses from all the other groups. … So that was like a project that we didn't get very much direction whatsoever and you could make anything you want, but there's still like solutions that are better or not as great. So I mean there's no right answer, but as long as things work, like okay this is the best one because of this and this and this.

4.4.6 Differences in Category 6 and Category 7

The major difference when moving into the most comprehensive way of experiencing MSPs, Category 7, is the internalization of the multiple perspectives involved in engaging with ill-structured, open-ended problems. This goes beyond revealing the ideas of others to allowing an understanding of those ideas to change the students' own way of thinking. The descriptions of experiences that have contributed to this category include an element of personal growth that extends beyond the immediate design experience. The internalization of multiple perspectives causes personal growth that will change the way that students experience future MSPs.

To start, although the inclusion of personal growth makes this the most comprehensive category within the outcome space, the fact that the task needs to be completed is still included within the category. Matt acknowledges that and then Shaun goes on to demonstrate how that grade, or seeking information solely to earn that grade, is not the focus of the experience.

> Matt: So if I take responsibility, I am doing my part of the work. I am telling my group look, I am doing the work timely and the work properly. I am doing the work with commitment. They obviously know that if this guy is doing it, we need to do it with commitment. He is working for the grade, we are working for the grade. He's not gonna get it without us and we're not getting without us. And they're obviously realize that if he doesn't do anything, they aren't gonna get a good grade. So if I'm doing my work, I think that makes them realize that, okay, we have some responsibility too. So I think that is why I like to take responsibility.

> Shaun: Every question we've had for [the instructional team], they kind of just…I mean they don't really tell you much, I feel like. They just, it's all up to you. You can't really ask questions, I feel like, unless it's just like how do I submit this on Blackboard? Like which folder do I need to turn it in to. I feel like when you're designing the problem, it's all up to and your group. You're not gonna

> have help from them. Because, I mean, every question we've asked, I mean they really don't, they can't tell you anything. They can't tell you how to come up with the solution because that's up to you. So. I mean, interacting with the TAs, professor, really hasn't been one of the big points of the class.

Similar to several of the other more comprehensive categories, the participants whose descriptions of their experiences contributed to Category 7 also acknowledge the transition from engaging with only SSPs. Shaun describes how it has been weird for him, but only because it is new and he has embraced the challenge. Quinn also describes her experience of embracing the challenge so that it does not inhibit her from experiencing MSPs in a more comprehensive way.

> Shaun: Uh, it was kinda weird. I mean, I had never had any engineering experience before this, and the fact that they give you these problems that can just go any which way, it's kinda weird, I guess. Um, because I don't like, I don't know. I don't like having so many options to choose from and it's weird for me to kind of weigh those options and decide on a best one because I want it to be the best one and I don't know if it's gonna be the best one, so. I don't know. Uh, but having those group members, I think, really helps. Um, because you can see their perspectives and it opens your eyes on new perspectives. And that really helps when you have these problems because you really see where other people come from and you can open your eyes to better solutions than what you would think of on your own. … Um, just the fact that I haven't had that before, like, I mean all of the classes I have taken, I never took any engineering courses like this in high school, um, never really part of any engineering groups. Um, I always had a set place that I needed to go that was told to us by the teacher, or whatever. So, I mean, it's weird for me in that I have just never had it before and it's a different, but good thing. So, yeah. I mean, I just never experienced it before.

> Quinn: It's not surprising to me. Um, I mean, I knew that coming in, knowing that it's important that I know how to do all these things, and know how to solve a problem, especially going into engineering, in such a good engineering school. So it's not surprising. It's, that doesn't make it any less difficult. It is hard. … [Pause] It's not that, like, I know it's expected of me, so it's not that I don't want to do it. It makes it – it's just, it can be hard because there's a lot that you have to know and so it causes me to have to stretch to parts of my mind maybe I haven't before. And so it makes it, it's more challenging than difficult.

This category is also inclusive of the focus of Category 3 to seek information in order to improve a design for a user. All three participants whose experiences contributed to Category 7 convey their awareness of the need to design with the user in mind.

> Matt: Unless you are not sure of the needs or the goals of what you have to achieve you can't really proceed forward, like you can't just, like keep hitting upon anything and just coming up with a project and just be lucky to get a project. Like, if you are, unless you are not sure what you need to do specifically, like we had to be sure we had to develop a toy or a game that is safe for the children that is engaging for the children. Now, keeping it engaging, we knew that the focus power of the children is pretty less, like, the teachers told us that for 6 months it's hardly 10 seconds, so we have to make sure that they learn the concept within this time. So, that, like if you don't know that we can't really work through the next 4 weeks developing the solution for the project.

> Quinn: I'm on one of the teams, and I'm working on building a website and so we had somebody – we showed them the website and they'd be like, okay this is confusing here because I was unable to understand how to search for something on this page or how to navigate this. And so in that point, we would take that back and be like, okay, somebody didn't know how to navigate through this page.

> Navigation is very important when it comes to a website so maybe we should ask somebody else, go through this page and see if you can navigate it or tell me what I need feedback on, and then I can, and if a lot of people are having a problem with it then that is something that I should change. And it may not change a lot, but a slight navigation tweak could change a lot of people's, like, how easy it is to use. … So if the audience of the project or the problem is being fixed they're whom you need to concentrate on and if, like, if it's for children, you don't want to make it extremely complicated because they may not understand. If it's an electronic device then you need to make it simple enough so a wide range of people who have different experiences with electronic devices, that they can, for a majority, can still use it. And if it's aimed older people, make it, if it's an electronic device, specifically, make sure that it's more, that it's easy to use for them, rather than a teenager who is extremely literate in using electronic devices.

> Shaun: Um, I think when developing a solution to one of these problems, it's gonna affect people in some way, and I think, with the parameters that you have for any of these questions given to you or if you have to find the solution, I think the way it affects people is probably one of the most important things. Because when you're designing a solution to a problem in society, I feel like the way that people will be affected by it is probably one of the biggest things because that's what you're designing it for. You're designing it so that the world is a better place, so that people have an easier time with doing something, or your solution helps them to more efficiently do something, stuff like that. So the way it helps people and affects people is really important, I think, when designing a solution.

As further evidence of the inclusion of less comprehensive categories, Matt describes the need to organize their team to agree on a common vision or goal and Shaun acknowledges the needs for the orchestration of logistics.

> Matt: Okay. So one of the problems that we faced when a solution had multiple problem was getting to one solution. Like one, like the team that I belong, the team I work with in engineering 131, uh…all four people are from different country, so there's a lot of diversity in there. That is beneficial at times when you get answers to, like, different answers and different ways of thinking, but you really get a problem, you really get, like a lot of problems, like coming up to one solution because everybody is having his own…everybody thinks that he is doing the right thing by giving his idea and that's really…causes a lot of problems coming to one solution.

> Shaun: Um, I feel like over the course of the semester my role has been not so much like, designing, and like coming up with the solutions, but like keeping everybody on track. Making sure everybody meets to do what they need to be doing. Because I feel like I am good when I'm in a position of like, leadership, and I think I'm good at keeping people on track and making sure they need to do what they need to be doing.

The inclusion of Category 6 is also provided through Matt's discussion of the way his team merged ideas when working on their design task in order to develop a better solution.

> Matt: I think that you cannot keep yourself in two boats at a single time. You cannot implement that and that. Obviously, if you can come up with a merged up solution, like we did recently in our design project, that is one to do it. But, like, if you don't have a single solution, he keeps on insisting, one person keeps on insisting that 'I want to take this solution' and the other says I want to over this, then that is really a lot of problem because he isn't willing to work on this side and this person isn't willing to work for the other one. So, then that gives a lot of…unless you have one agreed upon solution, you cannot really proceed. … So, then we came up with a merged idea, how to mix this second B thing with the A

> thing, so now it's like an A+B thing. So, it's like both the ideas—it's like A idea being properly implanted but 50%-70% of the B idea included into that.

Quinn goes beyond the theme of collaboration to describe how a decision matrix not only allows a team to select a design, but really facilitates their communication through that process.

> Quinn: You have your set guidelines, you know what you have to follow and you can't really. I mean there may be a difference of a ranking by one or two numbers but you're not going to fully disagree when you look at it in the big picture. It gave us, it helped us stay on topic because we wouldn't be concentrating on one part of it. We would get the number, be done, move on to the next one, and we wouldn't be jumping around as much, because you would be concentrated on, is this durable? And then think, why is it durable? Would it have flaws here? And so the team was just easy, we were able to communicate in an easy way.

In summary, the seven categories of description are qualitatively different based on the way the participant reacts to ambiguity and the role of multiple perspectives. Moving from a less to more comprehensive experience includes transitioning from attempting to eliminate ambiguity, to acknowledging it and then into accepting and even embracing ambiguity as a part of engaging with problems with multiple possible solutions. A requirement for a more comprehensive experience also includes the perspective that multiple perspectives are a contribution to the problem solving process as others' perspectives are valuable and by utilizing, understanding, or internalizing those perspectives the design is improved and the experience of the problems solver is more substantial. Evidence of the presented hierarchy comes from transcripts of more comprehensive categories including perspectives captured by the less comprehensive categories, but not maintaining those perspectives as the epitome of the experience. These findings are further connected to literature and implications are discussed in the following chapter.

CHAPTER 5. DISCUSSION

5.1 Introduction

In this study, I used phenomenography as a methodological framework to explore the qualitatively different ways that first-year engineering students experienced problems involving multiple possible solutions. The results of my analysis include seven different ways of experiencing these problems, and the axes of key variation that provide a logical order to the categories include the ways in which students react to ambiguity as well as the role of multiple perspectives in the problem solving process. Details of how each category was placed in relation to these categories are included in the previous chapter. This chapter includes a discussion of the ways in which the outcome space relates to previous literature as well as implications for designing problem solving experiences for engineering students. I also provide the limitations of the study as well as my thoughts on future work.

5.2 Axes of Variation

My analysis resulted in two axes of variation: reaction to ambiguity and role of multiple perspectives. These axes are distinct from one another as ways of understanding less and more comprehensive ways of experiencing MSPs. However, the axes are not independent. Rather, they are linked because the recognition that multiple perspectives are valid when defining or engaging with an ill-structured problem is linked to understanding that the problem will contain ambiguity, in part, as a result of those varying perspectives. These two features of experiencing MSPs have been identified as critical, which creates rationale for drawing students' attention to them specifically (Marton, 2014). In other words, this study suggests that if we want students to experience ill-structured problem solving in powerful ways, we must draw their attention to how they react to ambiguity as well as their understanding of the roles of multiple perspectives. Additional discussion of each axis is provided next.

5.2.1 Reaction to Ambiguity

The horizontal axis of the outcome space organizes the different ways of experiencing MSPs by the way the participants describe their reaction to ambiguity throughout the problem solving process. Here, the word ambiguity refers to all aspects of the types of problem being investigated in this study, as presented in the literature review, including a lack of information given, ambiguity throughout the problem solving process, multiple possible answers, and various ways to evaluate solutions to the problem. This finding supports the work of Jonassen by reinforcing that all of these aspects of ill-structured problems are influential in the experience of students learning to engage with such problems. In particular, the identification of reaction to ambiguity as an axis of variation confirms that engaging with problems with multiple possible solutions is qualitatively different from other problem-solving experiences where there is limited or no ambiguity. While the literature review emphasized "ambiguity" as something problem solvers navigate as a function of the process, my findings reveal that all four of the key aspects of engaging with ill-structured problems convey ambiguity to the learners, and their reaction to it is a theme of expanding awareness for them. Similarly, Rittel and Wibber's (1973) discussion of societal "wicked" problems are characterized by multiple properties of distinguishing problem types: no definitive formulation, no stopping rule, no single, right or wrong answer.

Moving from less to more comprehensive ways of experiencing an MSP can be interpreted as increasing in acceptance of the ill-structured, or ambiguous, nature of engineering problem solving. Specifically, this includes an initial transition from treating MSPs as though they were SSPs and trying to eliminate any ambiguity to acknowledging that ambiguity is a part of engineering work. Another transition was observed when students progressed into accepting ambiguity and finally embracing the ambiguity as an integral part of the problem solving process. My analysis resulted in the identification these of two transition points on this axis between Categories 1 and 2 and again between Category 2 and the remaining, more comprehensive categories. These transitions can also be differentiated by the perceived source of ambiguity. For example, in Category 1, students perceive the ambiguity as something created by the instructors and not a relevant part of engineering work. The transition into Category 2 includes students acknowledging that ambiguity is not just falsely created within the classroom, but is a valid part of engineering work that they believe they will need to learn to navigate. Movement through the next transition and into Category 3 marks students accepting that the source of ambiguity is inherent to the ill-structured problem solving experience itself, which is characteristic of engineering work.

Between the two transition boundaries, the way of experiencing ill-structured problems as transition, Category 2, aligns well with Meyer and Land's (2006) description of liminality. Liminality is a phenomenon related to engaging with trouble some knowledge, which may result if students have difficulty understanding a threshold concept. Liminality may result in students' understanding being demonstrated as a sort of mimicry (Meyer & Land, 2006), which is supported by my findings. Category 2 includes students who explicitly describe their difficulty transitioning into accepting ambiguity. By considering the acceptance of ambiguity to be a threshold concept, these students can be considered to be in a state of liminality. In other words, they are in between Categories 1 and 3; they have an awareness of ambiguity as a part of engineering problem solving, but their understanding of how to act on that awareness is still in flux. For example, Will describes her experience of working through the design process as motivated by following directions; only towards the end of the experience beginning to see how she will need to learn to be more accepting of ambiguity in the future as an engineering student. There is a tension between being dissatisfied with eliminating ambiguity (you can't just ask the teacher all the time), but there is not yet an acceptance of the ambiguity, resulting in a state of liminality. This captures the way that engaging with a threshold concept can be "experienced as a transition in terms of sense of self" (Meyer & Land, 2006, p. 19). Students may need to reconcile their idea of what engineering problem solving is and acknowledge their need to accept ambiguity as a part of their development as problem solvers.

The existence of liminality suggests that students may benefit from multiple opportunities to engage with MSPs. The transcripts within Category 2 indicate an awareness of the need to accept ambiguity, which may occur with additional opportunities to go through the process over time. This finding supports the curricular approach of providing engineering students with cornerstone design opportunities—if students experience liminality in capstone design, they may not experience engineering problem solving in a comprehensive way before they are granted their degree. The variation captured here (five of the seven ways of experiencing include an acceptance of ambiguity) indicates that many students are capable of accepting and embracing ambiguity during their early experiences with MSPs. This suggests that the acknowledgement and acceptance of ambiguity is not necessarily troublesome knowledge for many students; only four participants experienced MSPs in a way that did not include a minimum of acknowledging ambiguity as an inherent part of the engineering problem solving process. Therefore, it is likely more appropriate to refer to this finding as a transition rather than a threshold.

While all students should have their attention drawn explicitly to the ambiguous nature of ill-structured problems, additional scaffolding to support students through this transition may include providing other resources for students to gain an acceptance of the ambiguous nature of engineering work. For example, guest speakers from industry may be able to convey this through descriptions of their everyday experiences as engineers. First-year students may also benefit from hearing from upper-level students about how their capstone design projects required them to navigate ambiguity. Ensuring that students cross the this threshold is crucial; as shown in the outcome space, students do not start to have more comprehensive experiences along the vertical axis until their experiences include an acceptance of ambiguity.

5.2.2 Role of Multiple Perspectives

The vertical axis of the outcome space organizes the qualitatively different ways of experiencing MSPs according to the perceived role of multiple perspectives in the problem solving process. This dimension adds an important key factor to our understanding of students' experiences with ill-structured problem solving. While the horizontal axis, reaction to ambiguity, was well aligned with the nature of the problems, as discussed in the literature review, this key source of variation in experience, engaging with others, is a different, but related consideration when designing learning environments for first-year engineering students. The way that students experience the role of others demonstrates the importance of the social aspect of engaging with ill-structured problems. As a design team generates multiple problem solutions to satisfy an evolving problem space, they are engaging in design as a social process of navigating and negotiating their individual perspectives to reach a shared vision (Bucciarelli, 1994). This work revealed that the way students perceive the multiple perceptions present throughout the problem solving process (both outside and within their design team) as a key factor in the different ways of experiencing ill-structured problem solving.

Moving from a less to a more comprehensive experience in this regard is represented in the data as gaining an increasing appreciation for the value of working with multiple perspectives and the ability of those perspectives to inform your own thinking. Specifically, the least comprehensive way of experiencing ill-structured problems focuses on an alternative perspective as something that exists outside the group and holds some desired truth-value, which is linked to personal epistemology and discussed further in Section 5.3. For example, David describes his struggle to understand what the teacher wants in order to develop his work in a way that will satisfy that external perspective. Previous research from Downey and Lucena (2003, p. 171) also documented such a perspective in that engineering students "have come to relate to most instructors narrowly as functionaries who simply transmit the knowledge students need on tests. Engineering instructors are not to serve as independent sources of reflection and interpretation. Students know the curriculum was established by some past authorities and the truth or validity of its knowledge is no longer subject to question or reflection."

The focus on an external perspective that exists outside the designer also includes the user or consumer. While this is qualitatively different than the aim to determine what the teacher wants to inform your problem solving, it still revolves around seeking an outside perspective to guide your work. From Category 3, Karl and Oliver both describe the importance of seeking the perspective of those outside sources in order to iterate on an existing design in a way that improves it from the perspective of the user. The practice of considering the user is considered a fruitful design behavior, but it is limited in the sense that it does not acknowledge the additional perspectives brought to the process by the design team members.

The remaining and more comprehensive ways of engaging with multiple perspectives include a focus on the multiple perspectives within the design team. Category 4 experiences ill-structured problem solving as requiring management of these differences in order to make progress. This is in alignment with reviews of undergraduate reflections, which documented the perspective that engineers have to put up with explaining their ideas to others (Dunsmore, Turns, & Yellin, 2011). Category 5 crosses what I have identified as a major threshold within the outcome space into a way of experiencing MSPs that views multiple perspectives as advantageous to the problem solving process. Category 6 focuses on persuasion, which has been identified as a key characteristic of design (Cross, 1999). Finally, Category 7 goes beyond accepting multiple perspectives to understanding those perspectives in a way that allows the learner to integrate them into their own understanding.

As with the horizontal axis of reacting to complexity, the framework of threshold concepts (Meyer & Land, 2006) aids in interpreting source of variation in students' experiences with ill-structured problems. The threshold of accepting multiple perspectives as a productive part of ill-structured problem solving divides Categories 1-4 from Categories 5-6. The experiences described have distinct differences in the way they portray the role of multiple perspectives. The less comprehensive ways of experiencing do not describe an awareness of the benefits of multiple perspectives or the relativity of knowledge. In contrast, the more comprehensive ways of experiencing portray awareness of the essential contribution of multiple perspectives to a more well-rounded design and even personal growth as a result of engaging perspectives other than your own. These more comprehensive ways of experiencing align with the opinions of experts designers, which describe the engineering design process as "open, multi-participant, and multidisciplinary, in which the engineer-designer is not the sole source of design expertise" (Mosborg et al., 2005, p. 20).

Another researcher, Hsu (2015), also found that role of dealing with differences within team members was a source of critical variation in her phenomenographic study on the experience of students working in interdisciplinary teams. The recognition of navigating and learning from multiple perspectives is critical for working with ill-structured, open-ended problems, which this study identified as a threshold concept within the experience of first-year students engaging with engineering design. As such, learning environments should be designated to draw students' attention to their own perceptions of the role of multiple perspectives.

5.3 Personal Epistemology

The major transition and threshold identified in the outcome space of this study (accepting ambiguity and appreciating multiple perspectives) are corroborated by previous research on epistemological development. Epistemology is the study of how people perceive the nature and justification of knowledge (Hofer & Pintrich, 1997). In general, research in this area has revealed that as individuals develop, they transition through distinct stages from an absolute way of viewing knowledge as wrong or right and coming solely from authority figures to a more sophisticated view of knowledge, which recognizes multiple perspectives and the contextual nature of knowledge. For example, Perry's model (1970) starts from a dualistic perspective characterized by a belief that problems always have a right or wrong answer and that authorities hold all knowledge. Progression towards multiplicity includes acknowledging that different perspectives exist and can be true within particular contexts.

This sort of developmental progression aligns with the transition and threshold I have identified in this outcome space. Ways of experiencing that are below the identified transition and threshold include seeking the right way to solve the problem from relevant sources or examples, while the ways of experiences beyond these boundaries recognize their peers as sources of knowledge and the need for understanding of others and justification of design decisions.

5.4 Implications and Future Work

This research demonstrates that within a single university, even a small sample of first-year engineering students represent a range of experiences for engaging with problems with multiple possible solutions. This means that learning environments intended to provide meaningful experiences for early engineering students must be designed in order to accommodate this range of experiences. In particular, the experiences should include a focus on helping students to navigate a transition and cross an important threshold for ill-structured problem solving: accepting ambiguity and learning to see value in multiple perspectives when engaging with ill-structured problems. The observation of many students who, in their first year of engineering study, already had experiences that were beyond these crucial boundaries demonstrates that such students are very capable of having meaningful learning experiences beyond well-structured problems. In other words, this work implies that engineering programs do not need to wait until students are in their upper-level courses to provide them with ill-structured learning experiences.

This work also points to additional areas of research that if studied, would further our understanding of the ways in which first-year engineering students experience engaging with ill-structured, open-ended problems in powerful ways. For example, what sorts of design tasks promote more comprehensive ways of experiencing problems with multiple possible solutions within engineering education? This research has identified a range of possible ways of experiencing, but does not provide generalizable evidence for why some students have more comprehensive experiences than others. By revealing that the abilities to accept ambiguity as well as appreciate multiple perspectives are important limiting factors for students, future research may seek to understand if particular design experiences promote these ways of experiencing. In addition to specific aspects of particular design tasks, further work on how the dynamics of a design team influence students' view of the roles of multiple perspectives when engaging with problems with multiple possible solutions is of interest to this thread of research.

5.5 Limitations

As with any qualitative research, the results of this study are limited to the sample of the population that participated. While this sample was gathered to maximize variation across relevant demographics such as race, gender, immigration status, and course of enrollment, the sample was limited to a single university. In addition, the analysis was conducted by a single researcher, which has been advised against by some researchers with experience in phenomenographic analysis (Bowden & Green, 2005). While I did consult with other researchers throughout the process, I was the only researcher who had in-depth familiarity with the data in its entirety.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary of Findings

This phenomenographic study analyzed the transcript data from semi-structured interviews with first-year engineering students about their experiences with problems that involved multiple possible solutions. The results of this analysis included seven descriptive categories of qualitatively different ways of experiencing such problems:

1. Completion: Engaging with MSPs is centered on completing the task in the context of a classroom setting. The focus is not on developing a design or using the design process, but rather on seeking information that will enable the student to successfully complete the assignment. Relevant perspectives to understand include clarifying what the instructor wants or discussing with students who have previously completed the course. This approach views working with others as an opportunity to divide and conquer and lacks an appreciation of teammates as sources of knowledge. Students attempt to eliminate ambiguity in order to make the problem more well-structured.
2. Transition: Engaging with MSPs is still classroom-centric, but this way of experiencing is aimed at learning from going through the experience. While the participants do seek information that will allow them to successfully complete the task, they also reflect on why they are being asked to engage with this sort of problem and how it is a transition from SSPs in their past. There is a tension between wanting enough information to ensure a successful project and realizing that they need to transition to working more independently. They acknowledge the need for ambiguity in engineering, and they articulate their future transition into accepting it.

3. Iteration: Engaging with MSPs is focused on trouble shooting and creating or improving an artifact by iterating on a design. Design decisions are made without an explicit process and typically as they are needed, informally. Relevant perspectives that help to navigate ambiguity include expert opinion as well as user needs. Once these perspectives are known, the designer can iterate on the design to make improve it. This way of experiencing crosses an important threshold into accepting ambiguity within problem solving.
4. Organization: Engaging with MSPs requires the resolution of multiple perspectives. This includes coordinating logistics and establishing a common goal for the team to work towards. While ambiguity is accepted and multiple perspectives are viewed as a function of that ambiguity, it is difficult to coordinate bringing the contrasting views to a single solution. Time spent navigating multiple perspectives should be kept to a minimum in order to make progress towards a solution.
5. Collaboration: Engaging with MSPs allows you to utilize the multiple perspectives to defining a problem and designing a solution for that problem. As a team, you can share your perspectives and determine the best idea or combination of ideas to form a solution. As a designer, you need to make an effort to listen and consider the ideas of others, who may be right despite their difference from you. This way of experiencing crosses a threshold to valuing the perspectives of others as they can be valuable to optimizing your design.
6. Reasoning: Engaging with MSPs means working with multiple perspectives to generate an optimized design. However, unlike Category 5, the result of this process isn't just a final design, but rather a design with accompanying justification. This way of experiencing shifts to accepting ambiguity to embracing it as a useful part of the process. By navigating both the ambiguity and the multiple perspectives, the design team can develop reasoning for their decisions. This is necessary to convince others why your solution is better than the other potential solutions and to "sell" or communicate your design to others, including non-technical individuals.

7. Growth: Engaging with MSPs and their ambiguity is valuable because the experience exposes you to multiple perspectives, which not only improves your design, but also expands your own thinking. You learn from your team through internalizing your understanding of their varying perspectives, and that understanding stays with you after the design is completed. MSPs are an opportunity for personal growth in becoming an engineer.

6.2 Summary of Discussion

The discussion of the findings revolved primarily around the identification of two themes of expanding awareness that characterize students' variation in experience of ill-structured problem solving. These two themes were the way that students described their reaction to ambiguity and their understanding of the role of multiple perspectives throughout the problem solving process. While each axis of variation was divided into four different ways of experiencing ill-structured problem solving as a function of that axis, the data revealed a major transition of accepting ambiguity and a major threshold of valuing multiple perspectives throughout the problem solving process. Interpreting the findings of this study through the use of troublesome knowledge and threshold concepts (Meyer & Land, 2006) resulted in two important boundaries to be crossed for students to experience ill-structured problem solving in more comprehensive ways. As key takeaways from the outcome space, it is helpful to consider that an inability to navigate across these boundaries may inhibit students from experiencing ill-structured problem solving in powerful ways.

In addition to identifying these two important boundaries, the framework of epistemological development was also strongly aligned with the outcome space. Specifically, research has linked epistemological development to problem solving. As individuals develop, they have been observed to move from dualistic thinking to acknowledging the contextual nature of knowledge, which was present in the qualitatively different ways that first year engineering students experienced ill-structured problems. The most comprehensive ways of experiencing problem solving characterized by this study included an acceptance of ambiguity and recognition of the utilization of multiple perspectives as a key strategy to navigate that ambiguity. Future work includes further investigation of how specifics of designing learning environments can help first-year engineering students to experience MSPs in ways that are beyond these boundaries and therefore more comprehensive.

6.3 Recommendations for Educators

The goal of this phenomenographic study was to develop an outcome space that was of practical use to individuals within engineering education. In particular, I was motivated to present my research in a way that provided direct recommendations for practitioners who teach engineering students to engage with problems involving multiple possible solutions. This section presents concrete recommendations based on the analysis and outcome space developed through this study.

I should emphasize, the outcome space is not intended to categorize any single individual. The descriptions provided do not fully capture any experience, but rather are amalgams of experiences that are similar to each other, yet different from others in terms of the key axes of variation that emerged through iterative analysis. This outcome space is not intended to pigeonhole students or to completely predict their behavior. Rather, practitioners are encouraged to consider the key identified boundaries in order to accommodate a potential range of experiences and also to promote opportunities for students to experience problem solving in more comprehensive ways.

6.3.1 Learning Environments

In response to the identified axes of variation, practitioners should consider the ways in which the ill-structured problem solving experiences they are facilitating require students to identify strategies for navigating ambiguity. The ambiguous nature of engineering design problems should be discussed explicitly so that students can, at the very least, transition from an experience most closely aligned with Category 1, where ambiguity is experienced as something that should be eliminated, to Category 2, where ambiguity is acknowledged as a part of engineering problem solving. To promote further development along this axis of variation includes the acceptance or embracing of ambiguity as a part of the problem solving process. Providing students with multiple opportunities to practice key design behaviors aimed at navigating ambiguity might facilitate such development. A wealth of key strategies for facilitating these behaviors, which include framing the problem, conducting research, practicing idea fluency, modeling the system, analyzing tradeoffs, iterating and reflecting, are detailed in literature (Crismond & Adams, 2012). The findings of this research also provides evidence in support of cornerstone design by demonstrating that first-year engineering students are capable of accepting and even embracing ambiguity within the problem solving process. As the outcome space shows, once students have accepted ambiguity as a part of the nature of engineering problem solving, they can also move towards more comprehensive experiences by developing an appreciation of multiple perspectives.

The identification of the second axis of key variation leads to the recommendation that students are expected to consider the problem and solution spaces from multiple perspectives. This begs a focus on facilitating effective team experiences so that students are given the time to engage with each other and reveal their different perspectives on the problem. An emphasis on utilizing multiple perspectives throughout the problem solving might also be achieved by designing learning environments where students are expected to share ideas, identify ways of evaluating those ideas, and recognize that a combination of ideas from multiple perspectives can strengthen their design. Most importantly, a goal of designing learning environments for first-year engineering students to engage with ill-structured problems is to facilitate their crossing of the threshold of appreciating multiple perspectives within their design team as an asset to the problem solving process. For example, student teams might be arranged in a way that allows each individual team member to bring a particular value to the group, which can be recognized by the peers in the team.

An emphasis on reacting to ambiguity and considering multiple perspectives should also inform the assessment strategies within classroom problem solving practices.

Assessment should be tailored to allow students to demonstrate their learning in relation to these two crucial aspects of engaging with ill-structured problems. Specifically, students may be able to demonstrate specific ways they navigated ambiguity and utilized or internalized the perspectives of others during their problem solving experience.

6.3.2 Student Reflection

Another concrete recommendation for practitioners based on the findings of this study is to provide opportunities for students to reflect on both of the crucial ways that experiences were observed to vary. Having identified a range of experiences, students can be asked explicitly to reflect on their on reaction to ambiguity as well as how they understand the role of multiple perspectives with respect to the outcome space presented in this work. Because this outcome space is developed from snapshots of experiences shared by the participants, it is completely possible that a student could have a separate experience, which might reveal their awareness of different parts of the outcome space, so multiple forms of reflection might prove useful. To identify what aspects of the learning environment informed how comprehensive their experience was beyond the scope of the study. Therefore, students should be asked to reflect on their own perceptions for multiple different experiences and what aspects of those experienced helped them to accept ambiguity and appreciate multiple perspectives. The outcome space can be used as a tool to facilitate that reflection, especially if the sample in this study is representative of the population.

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APPENDICES

Appendix A: IRB Human Subjects Approval

PURDUE
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HUMAN RESEARCH PROTECTION PROGRAM
INSTITUTIONAL REVIEW BOARDS

To:	SENAY PURZER WANG
From:	JEANNIE DICLEMENTI, Chair Social Science IRB
Date:	08/25/2014
Committee Action:	**Exemption Granted**
IRB Action Date:	08/25/2014
IRB Protocol #:	1408015150
Study Title:	First Year Engineering Students' Experiences with the Introduction of Ill-Defined Problems

The Institutional Review Board (IRB) has reviewed the above-referenced study application and has determined that it meets the criteria for exemption under 45 CFR 46.101(b)(2) .

If you wish to make changes to this study, please refer to our guidance "**Minor Changes Not Requiring Review**" located on our website at http://www.irb.purdue.edu/policies.php. For changes requiring IRB review, please submit an **Amendment to Approved Study** form or **Personnel Amendment to Study** form, whichever is applicable, located on the forms page of our website www.irb.purdue.edu/forms.php. Please contact our office if you have any questions.

Below is a list of best practices that we request you use when conducting your research. The list contains both general items as well as those specific to the different exemption categories.

General

- To recruit from Purdue University classrooms, the instructor and all others associated with conduct of the course (e.g., teaching assistants) must not be present during announcement of the research opportunity or any recruitment activity. This may be accomplished by announcing, in advance, that class will either start later than usual or end earlier than usual so this activity may occur. It should be emphasized that attendance at the announcement and recruitment are voluntary and the student's attendance and enrollment decision will not be shared with those administering the course.
- If students earn extra credit towards their course grade through participation in a research project conducted by someone other than the course instructor(s), such as in the example above, the students participation should only be shared with the course instructor(s) at the end of the semester. Additionally, instructors who allow extra credit to be earned through participation in research must also provide an opportunity for students to earn comparable extra credit through a non-research activity requiring an amount of time and effort comparable to the research option.
- When conducting human subjects research at a non-Purdue college/university, investigators are urged to contact that institution's IRB to determine requirements for conducting research at that institution.
- When human subjects research will be conducted in schools or places of business, investigators must obtain written permission from an appropriate authority within the organization. If the written permission was not submitted with the study application at the time of IRB review (e.g., the school would not issue the letter without

proof of IRB approval, etc.), the investigator must submit the written permission to the IRB prior to engaging in the research activities (e.g., recruitment, study procedures, etc.). This is an institutional requirement.

Category 1

- When human subjects research will be conducted in schools or places of business, investigators must obtain written permission from an appropriate authority within the organization. If the written permission was not submitted with the study application at the time of IRB review (e.g., the school would not issue the letter without proof of IRB approval, etc.), the investigator must submit the written permission to the IRB prior to engaging in the research activities (e.g., recruitment, study procedures, etc.). This is an institutional requirement.

Categories 2 and 3

- Surveys and questionnaires should indicate
  - only participants 18 years of age and over are eligible to participate in the research; and
  - that participation is voluntary; and
  - that any questions may be skipped; and
  - include the investigator's name and contact information.
- Investigators should explain to participants the amount of time required to participate. Additionally, they should explain to participants how confidentiality will be maintained or if it will not be maintained.
- When conducting focus group research, investigators cannot guarantee that all participants in the focus group will maintain the confidentiality of other group participants. The investigator should make participants aware of this potential for breach of confidentiality.
- When human subjects research will be conducted in schools or places of business, investigators must obtain written permission from an appropriate authority within the organization. If the written permission was not submitted with the study application at the time of IRB review (e.g., the school would not issue the letter without proof of IRB approval, etc.), the investigator must submit the written permission to the IRB prior to engaging in the research activities (e.g., recruitment, study procedures, etc.). This is an institutional requirement.

Category 6

- Surveys and data collection instruments should note that participation is voluntary.
- Surveys and data collection instruments should note that participants may skip any questions.
- When taste testing foods which are highly allergenic (e.g., peanuts, milk, etc.) investigators should disclose the possibility of a reaction to potential subjects.

Appendix B: Participant Survey

PURDUE
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What is your age? (in years)

What is your sex?

- ◯ Male
- ◯ Female
- ◯ Prefer not to identify

What is your race/ethnicity? Please check all that apply.

- ◯ White
- ◯ Black or African American
- ◯ American Indian or Alaska Native
- ◯ Asian
- ◯ Native Hawaiian or Other Pacific Islander
- ◯ Prefer not to Identify

What is your student status?

- ◯ Domestic
- ◯ International
- ◯ Prefer not to identify

Are you currently enrolled in ENGR 131 for the first time? If no, please explain.

- ◯ Yes
- ◯ No

What is your intended major?

- ○ Aeronautics and Astronautics
- ○ Agricultural and Biological Engineering
- ○ Biomedical Engineering
- ○ Chemical Engineering
- ○ Civil Engineering
- ○ Construction Engineering and Management
- ○ Electrical and Computer Engineering
- ○ Environmental and Ecological Engineering
- ○ Industrial Enigneering
- ○ Materials Engineering
- ○ Mechanical Engineering
- ○ Nuclear Engineering
- ○ Other ______

Which of these other experiences have you had? Please check all that apply.

- ☐ EPICS
- ☐ High School Engineering
- ☐ Engineering Camp
- ☐ Robotics Team
- ☐ Learning Community ______
- ☐ Other ______

Where did you attend high school (or the equivalent)

- ○ United States (please provide state) ______
- ○ Other (please provide country) ______

If you are interested in participating in a voluntary one-on-one interview, please provide your name and email so that you can be contacted to schedule an interview. (e.g. Jane Doe, jdoe@purdue.edu)

______

0% [__________] 100%

>>

Appendix C: Demographic Information of Participants

Pseudonym	Age	Sex	Race	Student Status	ENGR Course	First Time Enrolled?	Intended Major	Previous Engineering Experiences: High School Engineering	Engineering Camp	Robotics	Learning Community	Other	None	HS Education
Alex	18	Male	White	Domestic	131	Yes	ChE	X						Connecticut
Bentley	19	Male	White	Domestic	131	Yes	ABE	X						Indiana
Casey	19	Female	White	Domestic	131	Yes	CE	X		X	X			Texas and North Dakota
David	20	Male	White	Domestic	132	No	IE				X			Indiana
Elliot	18	Male	Black or African American	Domestic	131	Yes	AAE	X						Indiana
Fran	18	Female	White	Domestic	131	Yes	ME		X					Missouri
Geoff	18	Male	White	Domestic	131	Yes	ME					X		Illinois
Ha	20	Female	Asian	International	131	Yes	EEE				X			Vietnam
Izzy	18	Female	Native Hawaiian or Other Pacific Islander	Domestic	131	Yes	IDE		X					Indiana
Jack	19	Male	Asian	International	132	Yes	ECE						X	China
Karl	19	Male	Asian	Domestic	132	No	BME						X	Missouri
Larry	18	Male	White	Domestic	133	Yes	CE	X						California
Matt	19	Male	Asian	International	131	Yes	ME			X		X		Pakistan
Neil	18	Male	Prefer not to Identify	Domestic	131	Yes	AAE			X				Indiana
Oliver	19	Male	White	Domestic	131	Yes	AAE/Business				X			Illinois

Appendix C (continued)

Pseudonym	Age	Sex	Race	Student Status	ENGR Course	First Time Enrolled?	Intended Major	Previous Engineering Experiences						HS Education
								High School Engineering	Engineering Camp	Robotics	Learning Community	Other	None	
Pam	18	Female	Prefer not to Identify	International	131	Yes	ECE						X	Brazil
Quinn	18	Female	White	Domestic	133	Yes	EEE				X			Texas
Robert	18	Male	White	Domestic	131	Yes	ECE	X	X		X	X		Missouri
Shaun	19	Male	White	Domestic	131	Yes	Undecided						X	Indiana
Tiffany	18	Female	White	Domestic	133	Yes	ME			X				Indiana
Ulsa	18	Female	White	Domestic	131	Yes	CE				X			Indiana
Victoria	18	Female	Asian	Domestic	133	Yes	ECE	X	X	X	X			Virginia (D.C. Area)
Will	19	Female	White	Domestic	131	Yes	BME						X	Indiana
Xin	19	Male	White	Domestic	131	Yes	ECE	X						Indiana
Yellena	18	Female	White	Domestic	131	Yes	NuclE	X						Indiana
Zixi	24	Male	Asian	International	131	Yes	ECE					X		India
Anne	18	Female	White	Domestic	133	Yes	AAE		X	X				California

Appendix D: Interview Protocol

Interview Number:
Pseudonym:
Date:

Logistics
Hello! Thank you for volunteering to participate in this interview. First I want to let you know what to expect.

- Our conversation will be **recorded** and then transcribed verbatim. This allows me to revisit what was said accurately and eliminates the need to take notes frantically. Any **identifying information will be removed** from the transcript and the audio will be kept in a secured location.
- Your name will be replaced with a pseudonym--do you have a preferred **pseudonym** (for next letter)?
- I may take some notes along the way, so that I can keep track of things to follow up on without interrupting you.
- The interview should be about an hour and is completely voluntary—you can stop at anytime.
- You will receive the $15 at the end of our discussion.
- Do you have any questions for me before we begin? [Answer, start recorder]

Purpose

- Our goal today is for us to have a detailed discussion about your **experiences solving problems with more than one potential solution**.
- The discussion will inform my understanding of the experiences of first-year engineering students and will help future decisions about course design and how it can be improved for all students.
- I want to hear your own experiences— I am expecting that they will be different from the experience of others—there is **no right or wrong answer**.
    - Your experience = **what you did, why you did it, how you thought, felt**
- I aim to understand your perspective, so I will ask questions like "what do you mean by that?" These types of questions can be a bit awkward and may require you to reflect on what you've experienced, so I will purposefully leave long pauses after my questions. Take your time--if you need clarification, please let me know.

Throughout interview, remember:

- *Respond with "that's interesting" rather than "that's good"*
- *Use "tell me more about that," "you used the word X, what do you mean by that?"*
- *Make connections, "why do you think that's important in terms of problem solving?"*

<u>Experience with IDPs</u>

1. Can you please start by describing an experience you've had working on a problem that had more than one potential solution.

a. What did that experience **involve**?
b. **How did you go about working on this problem**?
c. Why did you do it that way?
d. Why was that **important**?
e. How did that make you **feel**?
f. What was **your role** as a student working on this problem?
   i. How did you interact with your instructor(s)? Why?
   ii. How did you interact with other students? Why?
   iii. What could've made these interactions better? Why?
g. How did you know if you had done well on this assignment?

Situated in Contrast to WDPs

2. Now I'd like to hear about how this experience compares to your experience working on problems with one right answer. Can you start by describing an experience you've had working on a problem that had one right answer?
   a. Use above prompts a-g as necessary

Reflection

3. How would you **compare** the experiences you've described?
4. How are the experiences **similar, different**?
5. How would you describe your experience **engaging with both**?
6. Based on what we have discussed, what would you say is the **relationship between the problem solving experiences** we've discussed?
7. What do you think is **important** about the problem solving experiences you've had?
8. How have your **perceptions** of problem solving changed?
9. What **qualities about you**—perhaps some way you are different from your peers—influence your experience problem solving?)
10. Is there anything else you would like to share to help me understand your experience?

Conclusion

11. What questions do you have for me?
12. Do you have any feedback for me that would improve the experience of the next participant?
13. Thank you! [pay $15, sign human subjects log]

Appendix E: Post-interview Reflection Guide

Interview Reflection Guide

Interview Number:

Pseudonym:

Date:

Brief Summary

Impressions/Nuances

Difficulties

“Bracketing?

VITA

VITA

Emily A. Dringenberg
School of Engineering Education, Purdue University

Education
B.S., Mechanical Engineering, 2008, Kansas State University, Manhattan, Kansas
M.S., Industrial Engineering, 2014, Purdue University, West Lafayette, Indiana
Ph.D., Engineering Education, 2015, Purdue University, West Lafayette, Indiana

Honors and Awards
2012-2015 NSF Graduate Research Fellow
2011 AmeriCorps Academic Award, Teach For America Service Completion
2008 "Outstanding Senior," selected by KSU Mechanical Engineering Faculty
2009 Teach for America Fellow, top 10% of 35,000 applicants nationwide
2008 FE (Fundamentals of Engineering) Certification
2006 MNE Foundation Scholar Award, Dow Chemical

Publications and Professional Presentations

Book Chapters:
Purzer, Ş., Moore, T. J., **Dringenberg, E**. (Under Review). Cognition and engineering: Learning transfer and knowledge building. In Y. J. Dori & D. Baker (Eds.), *Cognition, metacognition, and culture in STEM education.* Springer.

Refereed Conference Papers:
Dringenberg, E., Mendoza-Garcia, J. A., Tafur, M., Hsu, M., Fila, N. (2015). Using Phenomenography: What are Key Considerations when Selecting a Specific Research Approach? *Proceedings of the American Society for Engineering Education Annual Conference and Exposition, Seattle, WA.*

Chua, M., **Dringenberg, E.** (2014). Work In Progress: The Quest for the Mythical Phoenix: Attendee Narratives at an Engineering Education Faculty Workshop. *Proceedings of the Frontiers in Education Annual Conference, Madrid, Spain.*

Dringenberg, E., Chua, M. (2014). What Can Reflections From an "Innovation in Engineering Education" Workshop Teach Workshop Designers and New Faculty? *Proceedings of the American Society for Engineering Education Annual Conference and Exposition, Indianapolis, IN.*

Dringenberg, E. (2014). First Year Students' Understanding of Normal Distributions: A Preliminary Study of Previous Exposure, Self-Efficacy and Content Knowledge. *Proceedings of the American Society for Engineering Education IL-IN Regional Conference, Terre Haute, IN*.

Denick, D., **Dringenberg, E.,** Fayyaz, F., Nelson, L., Pitterson, N., Tolbert, D., Yatchmeneff, M., Cardella, M. (2013). STEM Thinking in Informal Environments: Integration and Recommendations for Formal Settings. In Proceedings of the *American Society for Engineering Education IL-IN Regional Conference*, *Angola, IN.*

Dringenberg, E., Wertz, R. E. H., Purzer, Ş., & Strobel, J. (2012). Development of the Science and Engineering Classroom Learning Observation Protocol. In Proceedings of the *American Society for Engineering Education Annual Conference and Exposition*, *San Antonio, TX.*

Dringenberg, E., Wiener, J., Purzer, Ş., Groh, J. (2012). Measuring the impact of engineering outreach on middle school students' perceptions. In Proceedings of the *American Society for Engineering Education IL-IN Regional Conference*. *Valparaiso, IN.*

Mondisa, J., Fila, N., **Dringenberg, E**., Zephirin, T. (2012). Work in Progress: A Case Study of the Types and Frequencies of Conflict in Engineering Design Dyads. *In Proceedings of the Frontiers in Education Annual Conference, Seattle, WA.*