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By Ming-Chien Hsu

Entitled
UNDERGRADUATE ENGINEERING STUDENTS' EXPERIENCES OF INTERDISCIPLINARY LEARNING: A PHENOMENOGRAPHIC PERSPECTIVE

For the degree of Doctor of Philosophy

Is approved by the final examining committee:

Monica Cardella

Robin Adams

Senay Purzer

Carla Zoltowski

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Approved by Major Professor(s): Monica Cardella

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UNDERGRADUATE ENGINEERING STUDENTS' EXPERIENCES OF INTERDISCIPLINARY LEARNING: A PHENOMENOGRAPHIC PERSPECTIVE

A Dissertation

Submitted to the Faculty

of

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by

Ming-Chien Hsu

In Partial Fulfillment of the

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of

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May 2015

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West Lafayette, Indiana

To my ama, for your love and big heart.

To my parents, for your never-ending support of my education.

To Stacy, for motivating me to be more free-spirited and creative.

To Ryan, for showing me what it means to be passionate about the research one believes in.

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ABSTRACT

Hsu, Ming-Chien. Ph.D., Purdue University, May 2015. Undergraduate Engineering Students' Experiences of Interdisciplinary Learning: A Phenomenographic Perspective. Major Professor: Monica Cardella.

Engineers are expected to work with people with different disciplinary knowledge to solve real-world problems that are inherently complex, which is one of the reasons that interdisciplinary learning has become a common pedagogical practice in engineering education. However, empirical evidence on the impact of interdisciplinary learning on undergraduates is lacking. Regardless of the differences in the scope of methods used to assess interdisciplinary learning, frameworks of interdisciplinary learning are imperative for developing attainable outcomes as well as interpreting assessment data. Existing models of interdisciplinary learning have been either conceptual or based on research faculty members' experiences rather than empirical data.

The study addressed the gap by exploring the different ways that undergraduate engineering students experience interdisciplinary learning. A phenomenographic methodological framework was used to guide the design, data collection, and data analysis of the study. Twenty-two undergraduate engineering students with various interdisciplinary learning experiences were interviewed using semi-structured protocols. They concretely described their experiences and reflected meaning associated with those experiences. Analysis of the data revealed eight qualitatively different ways that students experience interdisciplinary learning, which include: interdisciplinary learning as (A) no awareness of differences, (B) control and assertion, (C) coping with differences, (D) navigating creative differences, (E) learning from differences, (F) bridging differences, (G) expanding intellectual boundaries, and (H) commitment to holistic perspectives. Categories D through H represent a hierarchical structure of increasingly comprehensive way of experiencing interdisciplinary learning. Further analysis uncovered two themes that varied throughout the categories: (i) engagement with differences and (ii) purpose and integration. Students whose experiences lie outside of the hierarchical structure need to engage difference in a positive manner and also have a purpose in engaging differences in order to experience interdisciplinary learning in a more comprehensive way. The results offer insights into the design of curriculum and classroom interdisciplinary experiences in engineering education.

CHAPTER 1. INTRODUCTION

1.1 Introduction

Important real world problems are inherently complex. Interdisciplinary practice, "*a process of answering a question, solving a problem, or addressing a topic that is too broad or complex to be dealt adequately by a single discipline or profession… [which] draws upon disciplinary perspectives and integrates their insights through construction of a more comprehensive perspective*" (Julie Thompson Klein & Newell, 1997), is required in solving many problems in order to bring together diverse perspectives and expertise.

The interdisciplinary approach arose due to "misfits" among needs, experience, information, knowledge represented by disciplines (Julie Thompson Klein, 1996). Understanding and solving those problems requires knowledge and perspectives from different disciplines. Interdisciplinary research and learning has been recognized as a way to further knowledge production and problem-solving (National Academy of Sciences, National Academy of Engineering, & Institute of Medicine, 2004). Despite being described as unreflective of problem choice or the epistemology of the disciplines used engineering practice has been recognized as increasingly more interdisciplinary (National Academy of Engineering, 2004; National Academy of Sciences et al., 2004). Graduates of accredited engineering programs have to demonstrate ability to "function in multidisciplinary teams" (ABET, 2009), as it is assumed that they will be working with people with different disciplinary knowledge to solve problems in their professional life.

These above reasons have driven the inclusion of interdisciplinary learning in the engineering curriculum, and it has been discussed as learning both in a collaborative environment and at the individual level. While the collaboration perspective is invaluable to student learning as it promotes learning from different expertise and socially negotiating new meaning and knowledge, interdisciplinary learning has the potential to be used as pedagogy for higher-order learning, such as critical thinking, higher-order cognitive skills, tolerance to ambiguity, etc.

Literature of interdisciplinary began as value-driven rather than data-driven, but efforts have been made to understand the topologies of interdisciplinary learning program (Lattuca, Voigt, Fath, & Voight, 2004), characterization of interdisciplinary programs (Knight, Lattuca, Kimball, & Reason, 2013), approaches to interdisciplinary teaching and learning (Nikitina, 2006), cognitive outcomes (Julie Thompson Klein, 2005; Repko, 2008), and assessment tools for interdisciplinary competency (Lattuca, Knight, & Bergom, 2013; Schaffer, Chen, Zhu, & Oakes, 2012). There still exists questions regarding what interdisciplinary learning entails and if and how it improves learning (Lattuca et al., 2004). More empirical evidence is especially needed to understand the landscape of the learning experience.

1.2 Statement of Problem

This study seeks to explore the nature of engineering students' interdisciplinary learning experience and the development of interdisciplinary skills. Particularly, how do students currently experience and understand interdisciplinary learning? Also, what are the more comprehensive ways that students understand and experience interdisciplinary learning? Exploring these two aspects would allow us to facilitate learning experiences based on current understanding. It will also allow us to understand the developmental journey to a more interdisciplinary way of thinking.

1.3 Research Questions

The study seeks to answer the question: What are the qualitatively different ways in which engineering students experience interdisciplinary learning (IDPLE)?

1.4 Significance of the Study

Exploring the critical differences of engineering students' interdisciplinary learning experience can delineate the space for various conceptions. The results of the study has the potential to inform the design of curriculum and learning instances to help students experience interdisciplinary learning in a more comprehensive way. The results of the study should reveal the nature of interdisciplinary learning experiences, which would have implication on how we think about interdisciplinary competencies.

1.5 Scope of the Study

The study explores the interdisciplinary learning experience of undergraduate students enrolled in the School of Engineering at a large Midwestern land-grant university. Interdisciplinary learning experiences that are curricular, co-curricular, design, research, internship, or co-op are all of interest.

1.6 Definition of Terms

Interdisciplinarity is a complex and evasive concept and for many decades, scholars have been making efforts to find constructs that characterize the topology of interdisciplinary practice (Lattuca, 2001; Newell, 1998; Salter & Hearn, 1997), resulting in different conceptualization and language use. For example, it has been characterized by the degree of conceptual integration (multidisciplinary, interdisciplinary, and transdisciplinary) (Newell, 1998) and also conceptual versus instrumental (Salter & Hearn, 1997). Lattuca (2001) characterized it regarding the questions that motivated the scholarship, such as informed disciplinarity, synthetic interdisciplinarity, transdisciplinarity, and conceptual interdisciplinarity.

For the purpose of this study, I use the term *interdisciplinary* as an all-encompassing term for working across different perspectives. During data collection, the term "interdisciplinary learning" was being referred to, but I let the participants know that there was no one definition for it. They were encouraged to mention any learning experience that they would consider interdisciplinary, and later on in the interview, they were asked to clarify in what ways the experience was interdisciplinary.

Words such as *discipline*, *field*, and *area of study* are sometimes used interchangeably (Donald, 2002, p. 7). These terms are used interchangeably in this study.

CHAPTER 2. LITERATURE REVIEW

Since the focus of the study is to study students' experiences of interdisciplinary learning, a literature search was conducted on interdisciplinary teaching and learning, particularly focusing on the research efforts under the topic.

2.1 Disciplines and Interdisciplinarity

Some argued that interdisciplinarity could not be understood and engaged without solid disciplinary grounding (Boix Mansilla & Duraising, 2007; Boix Mansilla, 2010). By learning what sets one discipline apart from another, we can grasp the possible exchanges and interaction during an interdisciplinary process and what students in interdisciplinary learning instances are experiencing.

One way to view the concept of discipline is from a structural point of view. Dressel and Marcus (1982, p. 89) identified five elements that constitute the organization and structure of the disciplines: (i) the substantive aspect, regarding the assumptions, concepts and principles of the discipline, (ii) the symbolism by which relationships are defined and elements identified, (iii) the conceptual structure, (iv) value regarding what is worth studying and how it should be studied, and finally (v) the relation to other disciplines. In her study of knowledge structures and trends across disciplines, Donald (2002) proposed four levels of analysis for understanding disciplinary differences: concepts, logical structure, validation criteria, and methods or modes of inquiry. In discussing the paradigms existing in qualitative research, Guba and Lincoln (1994, p. 108) used three perspectives to different one paradigm from another: ontology (what is the form and nature of reality), epistemology (what is the nature of the relationship between the knower and what can be known) , and methodology (how can an inquirer go about finding (observing, measuring, or revealing) what he or she believes can be known). Although Guba and Lincoln's discussion focus on qualitative paradigms, every discipline has underlying assumptions based on these three perspectives.

Another way to understand interdisciplinarity is from a socio-cultural standpoint (Bauer, 1990; Becher & Trowler, 2001; Becher, 1987; Donald, 2002). For example, Becher and Trowler (2001) described the notion of subscribing to a particular knowledge as a form of enculturation into a academic tribe. Not only do the problems, goals, and purposes of a discipline play an important role, but also the people in the community and the sets of meaning that they share. Language use is often the focus of discussion from this perspective (Bauer, 1990; Becher, 1987), Here, language use is symbolism plus the use of words and jargon. These words and jargon share meaning within a scholarly community. Word usage might entail different tacit meanings of the same word in different disciplines.

Therefore, interdisciplinarity can be seen as exchanges, interaction, borrowing negotiation and integration of (i) epistemological factors such as theories, methodologies, ways and validation and (ii) cultural factors such as value, discourse and language. Domain-specific epistemic beliefs are shaped by instructional environments and enculturation (Muis, Bendixen, & Haerle, 2006). In other words, as students enter a discipline, the epistemological and cultural factors of the discipline will start shaping how they know and what they know. Interdisciplinary exchange might be made difficult from the different ways of talking about things and getting to know things. Then, an interesting two-part question to explore from the interdisciplinary learning perspective is (a) how does such a learning environment fosters students' way of knowing, and (b) is this the way of knowing different from a single discipline way of knowing?

2.2 Characterizing Interdisciplinarity

The distinction between interdisciplinary collaboration versus other forms of collaboration is often muddled. Various efforts (Julie Thompson Klein, 1990; Lattuca & Knight, 2010; Lattuca, 2003; M. Miller & Boix Mansilla, 2004; R. C. Miller, 1982; Newell, 1998) were made to characterize interdisciplinary teaching, learning, and research into coherent conceptual frameworks. Often, categories were identified based on the integrative properties. Multidisciplinary efforts are often distinguished from interdisciplinary efforts in that it is additive rather than integrative (National Academy of Sciences et al., 2004). Participants leave the experience to continue on his or her own paths (Lattuca, 2001), and the contribution from the separate disciplines are visible both in the process and the product. In contrast, disciplinary contribution would be invisible in the interdisciplinary perspective. Although Borrego (2006) argued that engineers relied on others' expertise rather than engaging learning to reach true interdisciplinary collaboration, Miranda (Miranda, 2013) instead argued that the multidisciplinary approach in which each person remained in his or own boundary while collaboration allowed innovation. To add to the array of terms used, *transdisciplinarity* is often used to point to a problem-centered approach, which is arguably the approach that engineers would take to solve problems.

Instead focusing more on how different disciplines guides interdisciplinary learning and researching, Nikitina (2006) identified three strategies that faculty members used to teach interdisciplinary courses across the spectrum. Problem centering is identified as the strategies that applied fields such as engineering use. Its goal is to generate outcomes and change centering an ill-structured, real-world problem, which is different from the conceptualizing strategy used in humanities and the contextualizing strategies used in science. The two other strategies focus more on building coherent concepts and further understanding. Similarly, Ivanitskaya, Clark, Montgomery, and

Primeau (2002) proposed a scheme to characterize interdisciplinary programs based on the structure of integration. There could be interdisciplinary programs with no integration, interdisciplinarity around one central theme, and interdisciplinarity extended to other problems.

While these characterization schemes might be necessary to study the different kinds of exchanges between disciplines, for this study, I decided to include all learning experiences that were identified by the students as interdisciplinary, regardless of their definition. This would allow me to identify the full outcome space of interdisciplinary learning experience, including those that are less comprehensive but might help with our understanding of possible further development. This is in line with what Lattuca and Knight (Lattuca & Knight, 2010) suggested. When they interviewed engineering faculty members about what interdisciplinarity meant, they found that there was not a consensus on what that term meant. The faculty members' conceptions are even sometimes conflicting. Despite that, they advised against excluding activities based on whether they emphasize on collaboration or integration, since multidisciplinary interactions of students in engineering-only teams might contribute down the road to the development of integrative skills.

2.3 Barriers and Strategies

Challenges of interdisciplinary practice can be understood from the structural perspective or the socio-cultural perspective. From the structural perspective, differences between methods, values, and ways to validate claims would create barriers to interdisciplinary collaboration. From the socio-cultural perspective, the different disciplinary *tribes* (Becher & Trowler, 2001) use different "languages" and have different custom regarding day-to-day work. An example is a case study conducted by Richter and Parretti (2009); they found that in one interdisciplinary course organized around sustainable design, students failed to see connections between an interdisciplinary topic and their home department. Their study described (i) inability to connect interdisciplinary subjects to their own more narrowly defined fields of expertise, and (ii) failure to identify and value the contributions of multiple fields to complex problems as students' barriers to interdisciplinary learning and collaboration.

2.4 Interdisciplinary Learning Outcomes

Integration, synthesis, or connection of disciplinary perspectives is often argued as an ultimate outcome of interdisciplinary learning (Brown Leonard, 2007; Newell, 1994; Repko, 2008), which requires meaningful connection across knowledge domains. While some defined integration as a static outcome, more viewed it as a learning process (Dressel & Marcus, 1982; Haynes & Brown Leonard, 2010; Nikitina, 2005; Schaffer et al., 2012). Through the process of integration, other cognitive abilities are argued to be achieved, such as flexible thinking, deep learning, critical thinking, content retention, and self-directed learning (Ackerman & Perkins, 1989; Field, Lee, & Field, 1994). In the context of engineering education, eight interdisciplinary competencies were identified through literature review (Lattuca et al., 2013): awareness of disciplinarity, appreciation of disciplinary perspectives, appreciation of non-disciplinary perspectives, recognition of disciplinary limits, interdisciplinary evaluation, ability to find common ground, reflexivity, and integrative skill.

2.5 Process and Development of Interdisciplinary Learning

Interdisciplinary learning were explored through many different lenses, including socialization (Boden, Borrego, & Newswander, 2011), identity development (McNair, Newswander, Boden, & Borrego, 2011), engagement in programs (Newswander & Borrego, 2009), personal cognition and integration (Brown Leonard, 2007), collaboration and interaction, and development (Adams, Forin, & Srinivasan, 2010; Haynes & Brown Leonard, 2010). These perspectives were not exclusive. For example, the gain in cognition could be achieved through collaboration with people from other disciplines. Another example would be that identity could be developed through gain in cognition and socialization (Boden et al., 2011).

The following two frameworks within engineering characterized the evolution of individual or team cognition during a team process. In developing an assessment framework, Fruchter and Emery (Fruchter & Emery, 1999) proposed a model of a journey beginning from (i) being an island of knowledge, (ii) awareness of other discipline's goal and constraints, (iii) building appreciation, to (iv) understanding of other disciplines. The model was used to assess change in participation before and after an interdisciplinary course. The second framework, proposed by Schaffer, Lei, and Paulino (2008) after reviewing studies of teams, intended to present a progression within an engineering team learning cycle in three stages of progression. These three stages included self-identifying knowledge, skills, and potential contribution at the individual level (identification), linking and forming connection (forming), and adaption and integration (integration). Nikitina (2005) argued that the process of interdisciplinary learning is similar to communicative behavior of dialogue. Drawing from faculty member reflection on collaborations and thought process on integrating perspectives, three major cognitive moves are proposed: overcoming monodisciplinarity, provisional integration, and revising integration.

Boix Mansilla & Duraising (2007; 2010) focused exclusively on the cognitive perspectives without explicitly mentioning social influences. She argued that the four cognitive processes (establishing purpose, weighing disciplinary insights, building and leveraging integration, and maintaining a critical stance) articulated the kinds of knowledge being learned in interdisciplinary learning. Another theory that focused on the cognitive perspective was built upon the kinds of learning described by students in a liberal arts integrative program. Brown Leonard (2007) proposed different degrees of integration, suggesting that before true synthesis could happen, students sequentially needed to learn to apply, compare, and understand context. Internally, students needed to find coursework relevant to apply, identify multiple perspectives to learn, encounter conflict to understand context, and reconcile conflict to synthesize.

The above literature on interdisciplinary learning processes shared similarities but also differed in many other ways. First of all, disciplinary knowledge was the building block for all of the frameworks. The disciplines were described as the necessary preconditions for and foundations of interdisciplinarity, which was echoed by works by Repko (2008). However, both Nikitina's and Fruchter's frameworks proposed that the starting point was sufficient development of a single discipline (Fruchter & Emery, 1999; Nikitina, 2005); whereas the one proposed by Boix Mansilla and Duraising (2007) recognized the possibility of learning from several disciplines. Secondly, although the final state was integration and understanding of different disciplinary perspectives in all of the frameworks, two frameworks recognized that integration and understanding was dynamic and evolving (Boix Mansilla, 2010; Nikitina, 2005). Thirdly, in two of the frameworks, the role of *purpose* of integration was either specified or implicated (Boix Mansilla & Duraising, 2007; Ivanitskaya et al., 2002). Lastly, in the two frameworks developed within the context of interdisciplinary engineering team learning, "awareness" of the need to integrate preceded the integration process (Fruchter & Emery, 1999; Schaffer et al., 2008).

Different from the above frameworks that focused on cognitive steps taken to achieve integration, the developmental perspective revolved around the changes, whether continuous or in stages, that happen during learning. Adams et al. (Adams et al., 2010) aimed at describing the qualitatively different ways that practitioners experience interdisciplinary with a phenomenographic methodology. Different ways for the participants to experience practicing interdisciplinary work included: working together, intentional learning, strategic leadership, and challenge and transform practice (Adams et al., 2010). The results showed that interdisciplinary experience not only shaped cognition but also the ontological dimension. Another study that focused on the developmental perspective emerged from interviewing students from integrative liberal arts program. Haynes and Brown Leonard (2010) found that for beginning, on-going, and more mature students, the way they saw themselves and others in relation to interdisciplinarity changed. For example, agency in constructing interdisciplinary thinking increased with progression in program. Also, there was gradual realization of the limitation of "experts".

2.6 Assessment of Interdisciplinary Learning

Interdisciplinary learning is a complex phenomenon with many associated factors. Although possible outcomes of interdisciplinary programs and courses were proposed as discussed in an earlier section, it was argued that whether or not interdisciplinarity promotes learning was a difficult question to answer, since gains in skills and attributes might be attributed to other factors such as content, pedagogy, learner characteristics (Lattuca et al., 2004; Spelt, Biemans, Tobi, Luning, & Mulder, 2009). A review of interdisciplinary literature showed that research into teaching and learning was scarce (Spelt, Biemans, Tobi, Luning, & Mulder, 2009), and the reason was attributed to the complexity of teaching and learning interdisciplinary thinking.

In engineering education, few studies specifically examined whether interdisicplinarity contributes to learning. Borrego, Newswander, McNair, McGinnis, & Paretti (Borrego, Newswander, McNair, et al., 2009) used concept maps to assess integration of content knowledge from various disciplines in green engineering design based on comprehensiveness and correctness. Coso and Bailey (2010) assessed engineering students' responses to questionnaire on perceptions of interdisciplinary projects based on coding scheme built on the performance assessment framework that Boix Mansilla & Duraising (2007) developed from interview data with interdisciplinary program faculty and upperclassmen. Boix Mansilla & Duraising's framework focused on assessing interdisciplinary understanding based on grounding in disciplines, showing critical awareness of disciplinary limitations based on the goal of the approach, and integration across disciplines that enhanced understanding (Boix Mansilla & Duraising, 2007; Boix Mansilla, 2010). Also, Coso, Bailey, and Minzenmayer (2010) used similar coding schemes for analyzing think-aloud protocols of a design problem that required an interdisciplinary approach. Lastly, Frutcher and Emery (Fruchter & Emery, 1999) used their process framework of progressing from islands from knowledge to understanding to assess whether there was evidence of interdisciplinary learning in an architecture/engineering/construction interdisciplinary program.

A few studies used Likert-scale items to examine students' self-efficacy of interdisciplinary learning. In the first study, Lattuca and Knight (2013) developed self-efficacy scales for the eight engineering interdisciplinary competencies identified from the literature. After factor analysis, only three factors held up, including interdisciplinary skills, reflective behavior, recognizing disciplinary perspectives. With the instrument, they found differences between students of different engineering disciplines especially on their scores of interdisciplinary skills. In the second study, Schaffer et al (2012) also developed self-efficacy scales, but on three factors called identification, recognition, and integration identified in an earlier study (Schaffer et al., 2008). Although the definition of identification and recognition in Schaffer's study (Schaffer et al., 2012) roughly fit in what Lattuca and Knight (2013) called interdisciplinary skills factor in Lattuca and Knight's study, Schaffer's (Schaffer et al., 2012) instrument focused on learning in a team problem-solving environment. Instead, Lattuca and Knight (2013) focused on the relationship between engineering and non-engineering disciplines.

There are commonality and differences among these assessment studies. There are two variances regarding the characteristics of the assessment:

- Program or course specific (Borrego, Newswander, McNair, et al., 2009) versus general use (Lattuca et al., 2013)
- Team-environment (Schaffer et al., 2012) versus individual-focused (Borrego, Newswander, Mcnair, & Paretti, 2009; Coso et al., 2010; Coso & Bailey, 2010; Lattuca et al., 2013)

One thing in common among these studies on assessing interdisciplinary learning in engineering is the reliance on a model of interdisciplinary outcome, process, or performance, which is one of the three pillars of assessment (Pellegrino, Chudowsky, & Glaser, 2001) that would provide interpretation to the gathered evidence.

2.7 Summary

In the first section of the literature review, I concluded that an interdisciplinary learning environment could potentially provide opportunities to examine how individuals navigated the different epistemological and cultural factors within the different disciplines. In the second section of the literature review, I showed that there existed barriers to interdisciplinary learning due to differences in structural and socio-cultural aspects of disciplinary practices. I then explored intended learning outcomes and processes of interdisciplinary learning, whether they were derived empirically or conceptually. Lastly, I reviewed studies that assess the outcomes of interdisciplinary learning. I concluded that despite the differences in the scope of the assessment method (program specific versus general use and team-based versus individual), the assessment studies relied on frameworks that would allow data to be interpreted. However, it was not clear whether the frameworks currently existed could describe the ways that an engineering students experienced interdisciplinary learning, since most frameworks were derived from research faculty members' experiences (Nikitina, 2005) or synthesized from literature (Fruchter & Emery, 1999; Schaffer et al., 2008). There were exceptions. Adam's study (Adams et al., 2010) did include students as participants, but practitioner's experiences were a large part of the study. Furthermore, interdisciplinary experiences were framed as practicing experiences instead of learning. Another study that focused on students' experience was Haynes and Brown Leonard's study (Haynes & Brown Leonard, 2010), but the context of the study, integrative programs in liberal arts colleges, was very different from engineering experiences. Therefore, I studied the different way that undergraduate students in engineering experience interdisciplinary learning.

CHAPTER 3. METHEDOLOGY AND STUDY DESIGN

3.1 Introduction

In this chapter, I will introduce the methodological framework of the study, as well as the method used for the study. Moreover, I will demonstrate how the method, including study design, participant recruitment, data collection, and data analysis was guided by the methodological framework.

3.2 Using a Phenomenographic Approach

Since the goal of the study was to explore the qualitatively different ways students in interdisciplinary programs experience and understand interdisciplinary learning, a phenomenographic framework was chosen to guide the design of this study. Phenomenography is a naturalistic approach (Booth, 2001) described as a research approach with a strong interest in education and learning (Marton & Booth, 1997)

The tenet of phenomenography is that a phenomenon can be understood in a limited number of qualitative ways (Booth, 1997). The goal of the methodology is to unearth what those different ways of understanding are. This goal of the approach is achieved by uncovering what Marton (Marton, 1981) called “second-order perspective”, which means instead of researching (i) the subject themselves or (ii) the phenomena, the focus is on the interaction between the two. In other words, the interest is in describing the phenomena as the subjects see them, and describing the variation within those experiences (Marton & Booth, 1997). The approach focuses on collective experience of the sample group rather than individual experience, which means no one interview can be understood without others (Akerlind & Åkerlind, 2005). Whereas Marton and Booth (1997) adopted a realist philosophical underpinning to the phenomenon being studied, Richardson (Richardson, 1999) argued for a constructivist stance, meaning to see the oral accounts as a discursive and accounting practices rather than the conception of reality. Saljo (1997) also argued that the unit of analysis in phenomenography (ways of understanding) as ways of understanding, talking, and attempts at communicating in situated practice.

The outcome of a phenomenographic study is a critical variation in the experience called "categories of description" and that has an "inclusive structure" relating the different categories forming a hierarchical structure (Akerlind & Åkerlind, 2005; Marton & Booth, 1997). Marton and Booth (1997, p. 125) identified three criteria for the quality of a set of categories of description:

- "Each category should stand in clear relation to the phenomenon."
- "The categories have to stand in a logical relationship with one another."
- "Few categories should be explicated as is feasible and reasonable, for capturing the critical variation in the data."

Additionally, "themes of expanding awareness" are developed to describe the aspects that show the qualitatively different ways of awareness and experience. Together, the categories of description and the themes of expanding awareness forms the "outcome space".

Phenomenology and phenomenography differ in the following ways:

- Phenomenology deals with first-order experience with the phenomenon in question as the primary unit of analysis (Van Manen, 1990), while phenomenography with second-order experience with subject's experience of the phenomenon as the unit of analysis(Marton, 1981).

- The aim of phenomenology is to find the *essence* of the phenomenon. However, the aim of phenomenography is to find the critical *variations* of experiencing the phenomenon, and those experiences are temporary and transient (Marton & Booth, 1997).
- Phenomenology search for immediate experience and not conceptual thoughts, but phenomenography does not distinguish between the two. Phenomenography is interested in the relation between the subjects and the phenomenon regardless of the form that it manifests (Marton & Booth, 1997).

There are also distinctions between grounded theory and phenomenography. The grounded theory methods use “constant comparative method”, using open coding and axial coding to find themes and relationship between themes at the statement level (Patton, 2002). However, the analysis of a phenomenographic approach focuses on the transcript level. Moreover, grounded theory aims to build theories while phenomenography to describe variation of experience.

Since the goal of this study is to describe variations of students’ experience with learning in interdisciplinary settings, a phenomenographic approach is suitable instead of the phenomenology or grounded theory approach.

A wide array of studies used phenomenographic methods to investigate learning experiences in general (Marton & Säljö, 1976), such as engineering first year students' conceptions of learning (Marshall, Summer, & Woolnough, 1999), educator's conception of teaching and research (Åkerlind, 2004). Another direction is to use phenomenography to explore learning within a disciplinary context and on student conception of a subject matter, such computer programming (Booth, 2001), understanding of displacement and velocity in physics (Bowden et al., 1992), and conception of solubility in science (Ebenezer & Erickson, 1996).

In engineering education, phenomenography is an emerging methodology (Case & Light, 2011). Previous phenomenographic studies in engineering education include investigation of student understanding and conceptions of human-centered design (Zoltowski, Oakes, & Cardella, 2012), repetitive structures of programming languages (Bucks & Oakes, 2010), size and scale in nanotechnology (Swarat, Light, Park, & Drane, 2011). Regarding instructions in engineering, phenomenography was used to study experience of including simulations tools in instruction (Magana, Brophy, & Bodner, 2012). In the space of practitioners, some phenomenographic studies relating to engineering include practitioners' conceptions and understanding of interdisciplinary practice (Adams et al., 2010), design (Daly, Adams, & Bodner, 2012), work competency at a automobile manufacturing (Sandberg, 2000), and sustainable design (Mann, Dall'Alba, & Radcliffe, 2007).

3.2.1 Data Collection

Most phenomenographic studies include 20 to 30 participants (Daly et al., 2012; Mann et al., 2007). The participants are selected from the targeted population so there is as much variation in their experience. More data should be collected if there's suspicion that current collection does not represent full range of variation (Booth, 2001).

The primary sources of data in phenomenographic studies are usually interviews, while other kinds of data might be used to triangulate the findings, such as group interviews, observations, drawings, written responses, and historical documents (Marton & Booth, 1997, p. 132). Richardson (Richardson, 1999) argued that these different data collection methods have the same evidences status as oral accounts as there are simply different forms of discourse.

A phenomenographic interview uses detailed discussions on participants' concrete experience to uncover their understanding about certain aspect of the world. Having participants talk about concrete experience facilitates meaningful reflections about their awareness and values. Therefore, the follow-up questions should focus on eliciting meaning. Booth (2001) offered a few ways to help with understanding of the theme in focus: confirming meaning by returning to statements, following up with unexpected threads, unblock unexpected obstacles, and closing the interview by letting students express their view and questions. During the interviews, the interviewer should bracket his or her own assumptions, known theories, and earlier research findings in order to maintain "empathetic neutrality" (Ashworth & Lucas, 1998, 2000; Patton, 2002). Since interviewing is the only source of the data, pilot study is necessary to refine the questions for better flow. The pilot protocols of the proposed study are included in the next section.

3.2.2 Data Analysis

There are two schools of thoughts regarding data analysis of studies utilizing the phenomenography theoretical framework. The first perspective, based in Europe, focuses on pooling meanings from different transcripts with the same qualitative way of experiencing a certain phenomenon (Marton, 1983). In contrast, analysis of the data in the second approach is conducted at the level of the transcript, considering each experience as a whole (Akerlind & Åkerlind, 2005; Bowden, 2000). Also, each transcript is analyzed with respect to other interviews. During the analysis process, empathetic neutrality should also be exercised to bracket assumptions and pre-conceptions. The categories of descriptions should emerge from the data instead of being pre-determined (Bowden, 2000), although other researchers contested that by arguing that treating data analysis as merely discovery and no construction was problematic (Bruce, 2003; Walsh, 2000). An open mind should be kept during initial readings of the data, but subsequent reading will bring the focus on certain aspect of the data. The process of determining the categories is done by grouping and regrouping the data based on similarities and differences as perceived, focusing on one aspect at a time (Akerlind & Åkerlind, 2005).

Examining what researchers reported as actually happened during analysis, Akerlind (Akerlind & Åkerlind, 2005) synthesized the variation in phenomenographic analysis practice:

- Considering the whole transcript related to a particular issue versus selecting excerpts and quotes as representation of a certain aspect
- Individual work versus collaborative work
- Variation in the degree to which the structure of the outcome space emerge as directly as possible versus from the professional judgment of the researcher

Akerlind (Akerlind & Åkerlind, 2005) argued that validity and reliability check should be reframed within the context of the research approach. For phenomenography, she suggested using communicative validity checks (ensuring method and interpretation are regarded as appropriate by the research community or other individuals within the sample population) and pragmatic validity checks (if the study produces useful insights) to ensure validity. As for reliability, researchers must make clear to the readers the interpretive steps taken during analysis. Similar measures were also taken by Sandberg (2000).

3.2.3 Appropriateness for the Study

I chose to use phenomenography for the study because of the need for a framework for the area beyond prescriptive competencies and processes to further our understanding. Also, I need a methodology that would guide me to capture the breadth of students' experiences of interdisciplinary learning. While existing theoretical framework was used to explore interdisciplinary learning in engineering education, such as socialization and self-efficacy, we do not know students' learning experiences. As I was interested in exploring different ways engineering students experienced interdisciplinary learning instead of the essences of their experiences. My intention to explore the differences and variations in experience led me to the methodology of phenomenography.

I decided to use the "Australian" school of phenomenography as mentioned in Section 3.2.2 to consider whole transcripts. Quotes and utterances from an individual will be considered with respect to rest of the transcript. This approach would reduce the risk of the researcher trying to make sense of a quote regardless of the context from which they emerge, and it allow the transcripts to be understood as inter-related meanings (Akerlind & Åkerlind, 2005). Although phenomenography focus on the experience and not the individual, I do not believe that I can understand the experience without knowing more about the individuals' thoughts and other experiences. For that reason, I chose to use the "Australian" approach.

3.3 Research Method and Design

3.3.1 Sampling

The scope of the research was to explore variation of interdisciplinary learning experience of undergraduate students who were enrolled in the School of Engineering at a Midwestern public university, and therefore I used purposeful maximum variation sampling to recruit participants of the study. Participants were selected from students who had participated in learning experiences that they self-identified as interdisciplinary in nature.

In order to recruit participants with a various range of interdisciplinary learning experiences, I targeted various academic context with possible interdisciplinary learning opportunities, including the service learning program, global design program, engineering student organizations such as engineering without borders, academic programs such as interdisciplinary engineering, biomedical engineering, and environmental engineering.

Specifically, the goal was to recruit participants with experiences reflecting variations of the degree of integration, curricular characteristics, degree of engagement with others, gender and school affiliation. As interdisciplinary learning has been discussed from the perspectives of integration as well as collaboration, sampling reflected variation in the degree of integration and variation in the curricular characteristics. Furthermore, as there were a variety of activities besides project work that students would characterize as interdisciplinary learning experience, including experiences besides project work would captured the full range of student experiences. Lastly, I considered a distribution of gender and engineering school affiliation since past studies found differences in how participants of different gender and engineering school affiliation approached interdisciplinary problems (Coso et al., 2010).

The following are more details of the kinds of variation in experiences and demographic characteristics that I focused on when recruiting participants:

- Types of Interdisciplinary Learning Experience
    a. Degree of integration as informed by the interdisciplinary topology framework
        - Informed interdisciplinary experiences that are motivated by questions from a particular discipline but informed by other disciplines (Lattuca, 2003), such as cross-listed courses.
        - Synthetic interdisciplinary experiences that combine identifiable disciplines (Lattuca, 2003), such as a course that analyzes an event from the perspectives of engineering, sociology and art, as well as projects with discernable disciplinary components.
        - Transdisciplinary experiences that no longer associate with single disciplines but instead focus on concepts or methods that can be applied across disciplines (Lattuca, 2003), such as ones associated with concepts of sustainability or research experience. Another definition of

transdisciplinary experiences are ones shaped by consideration of particular context that might be social, cultural, environmental, etc. (Lattuca & Knight, 2010).

b. Curricular characteristics
    - Curricular- Project, which included any credit earning experience with project work
    - Curricular- Others, which included any credit earning experience without project work
    - Extra-curricular activities, such as competitions and club activities with imposed structures such as deadlines
    - Research
    - Internship, co-op, or other work experience
    - Informal, which encompassed less structured experiences such as Women in Engineering, residential life, study groups, social groups and undergraduate teaching

- The Degree of Engagement with Others, as informed by the integration versus collaboration outcomes of interdisciplinary work
    - No partners or clients
    - Projects with team members and local clients
    - Projects with geographically distributed team members or remote clients

Besides variation in the participants' interdisciplinary experiences, variation in the following demographic characteristics of the participants is also criteria for participant sampling:

- Gender
- Engineering school affiliation

Class standing is not emphasized as one of the criteria of variation, since the engineering students at the particular institution are places in a first-year engineering and do not declare major until the second year of school. Therefore, I assume that freshmen and sophomore might have less sense of disciplinary affiliation than upperclassman. However, their participation in the study is encouraged as long as they have self-identified participation in interdisciplinary learning experiences.

3.3.2 Participant Recruitment

Participants were recruited on the main campus of a Mid-western land-grant R1 university. Recruitment was conducted through flyers posted on bulletin board distributed on campus as well as emails requesting interdisciplinary course instructors and program coordinators to forward information to students. The recruitment email was also sent to administrators in academic departments (biomedical engineering, environmental engineering, interdisciplinary and multidisciplinary engineering), design team programs (service learning and global design programs), research programs (summer engineering undergraduate research program), and instructors of courses (including engineering and art department).

The recruitment email sent out to students include da link to a Qualtrics survey that asked the respondents to list the types of interdisciplinary learning experience that they have had, including course, project, research, co-curricular, work experience, and any other learning experience they considered interdisciplinary. The survey questions are included in the Appendix. The intent of the screening survey was (i) to make sure that the sampling criteria in 3.3 would be met at the end of the data collection process, and (ii) to serve as an opportunity for potential participants to reflect on what they considered as interdisciplinary learning experiences. Once an interested student responded to the Qualtrics screening survey, the researcher contacted prospective student to set up a time for interview through email. All students that took the survey and responded to the request to interview were interviewed.

The recruitment and data collection was conducted in the course of seven months beginning in April 2012. A second wave of recruitment was conducted in the late summer since more participants were needed with experiences (i) working with different others in geologically distributed or global locations and (ii) with no partners were needed. Focus was placed on the undergraduate research program and global engineering program, while continuing recruiting through the venues mentioned previously. This study included 22 participants that reflected the variation described in section 3.3. Summary of the demographic characteristics of the participants is displayed in Table 3.1, whereas demographic and learning experience characteristics by individual participants is demonstrated in Table 4.3.

Table 3.1 Summary of demographic characteristics of the participants (n=22).

Class Standing		Sex		Major		Ethnicity	
Freshmen	1	Male	11	AAE	1	Asian	7
Sophomore	1	Female	11	ABE	3	African American	2
Junior	7			BME	2	Caucasian	11
Senior	13			CE/CEM	3	Hispanic	2
				ChemE	2		
				ECE	3		
				FYE	1		
				IDE/MDE	2		
				ME	4		
				MSE	1		

3.3.3 Data Collection

The data collected for the study was semi-structured interviews. I conducted all the interviews; having one person do all the interviews is preferred in phenomenographic studies (Akerlind & Åkerlind, 2005), while Bowden (2005) argued the opposite. Before the interview begin, I communicated with the participants about the purpose of the interview (learning about the participants' interdisciplinary learning experiences), the procedure (asking them to describe 1 to 2 experiences then some reflective questions on what interdisciplinary learning means to them), and the definition (no predetermined definition of what interdisciplinary learning means but want them to describe whatever experience is relevant to them).

The design of the protocols is important since interviews were the only source of data for this study. The goal of the protocols was to prompt the participants to discuss their experience. Having participants begin by describing an experience rather than by answering the question "what is X (the phenomena)" was found to be eliciting outcomes that are more varied. Before each interview began, the interviewer communicated that there was not a predisposed conception about what interdisciplinary learning was and instead it was important to know how the participants defined and experienced interdisciplinary learning. The interview started with rapport-building conversations, moving into discussion on participants' concrete interdisciplinary experiences, and then reflective questions on meanings they associated with interdisciplinary learning. Follow-up questions interjected were asking for reasons, clarification for use of word, and asking for more example, including "what" and "how" questions to allow association with concrete experiences (Akerlind & Åkerlind, 2005) and also questions focusing on participants intention or purpose.

I prepared and revised the protocols through reading transcripts of other phenomenographic studies, such as the study of cross-disciplinary practices (Adams et al.,

2010) and human-centered design (Zoltowski et al., 2012). Reading transcripts of other phenomenographic studies allowed me to get familiarized with the flow of such interviews. Pilot tests were conducted first with two engineering students to test the protocols. Notes on the kinds of follow-up questions to expect were also made. After rewording some questions, further pilots were conducted with three participants from the target population. The goals of the pilot tests were to (i) have the researcher practice refraining making comments and adding new constructs to the material, (ii) test whether the protocols actually elicit comments on the topic, and (iii) test the sequences of the questions. I learned that I had to focus on eliciting meaning using the why and how questions on top of details of what the participants did in interdisciplinary learning experiences. I made modification to include a question to elicit "in what ways is the learning experience interdisciplinary". The first three interviews were included as part of the data analysis, since the overall structure of the protocol remained the same. The final interview protocols are displayed in the following pages:

Opening statements

Thank you for agreeing to participate in the study. I am a graduate student in Engineering Education and I am studying the nature of interdisciplinary learning experiences.

Reviewing sections on the consent form

Purpose

Procedure and duration

Risk and benefits

Compensation

Confidentiality

Voluntary nature of participation: I would like to remind you that there is no correct answer. I am interested in your experience.

Describing Experiences

Can you describe a learning experience you have had that was interdisciplinary in nature?

- What did that experience involve?
- Objectives? How were the objectives set?
- Who was involved (client/instructors/teammates)?
- What were their (your) roles?
- What was your interaction with (client/instructors/teammates)?
- How did you interact with other people in this experience?
- In what way is the learning experience interdisciplinary?
- Why was that so important? (If not clear from the previous conversation)
- What did a typical class/meeting/working day involve?
- (Reflect) What did you gain from the interdisciplinary aspect of the experience?
- (Reflect) Can you describe a challenge you faced? What did you do in this situation (concrete)?
- (Reflect) How is the experience different from other learning experience that is not interdisciplinary?
- What would you have done differently next time?

Other experiences

- Can you describe another learning experience you have had that was interdisciplinary in nature?
- How do you think this is a different interdisciplinary learning experience from we talked about earlier?

Summative questions

- What does it mean to you to be involved in an IDP learning experience?
- Do you think that your views on interdisciplinary learning have changed over time?

- If so, in what way?
- If not, why do you think this is?
- Can you think of a specific time or issue that challenged learning in an interdisciplinary setting?

Conclusion

- Do you have anything else you want to add about learning in the interdisciplinary context?
- Do you have any questions for me?

Additional Probes

Additional probes will be used with the following interview questions:

- That is interesting. Tell me more about that.
- What do you mean by X? (Guarding against assuming any terms the participant says)
- Could you give me an example?
- What other thoughts do you have?

3.3.4 Data Analysis

A certified medical transcriptionist transcribed the audio recordings of the interviews. When transcriptions were completed, the researcher listened to the recordings to check against the transcriptions. Before doing any analysis, the researcher read and reread the transcript to gain familiarity with each participant's narratives.

I started the analysis with ten transcripts collected at during the first wave of recruitment. At the third round of reading the transcripts, I began to take notes on the learning experiences each participants mentioned, why those experiences were interdisciplinary, and what it meant for individuals to be involved in interdisciplinary learning. On the fourth round of reading, I marked the themes that I noticed in each transcript. I made summery of each transcript to help manage the volume of data. The transcripts were then sorted into piles according to the similarities and differences of how the participants talked about their interdisciplinary learning experiences. The sorting was based on the evidence provided by the transcripts. Besides bracketing presuppositions, I also exercised empathetic understanding (Ashworth & Lucas, 1998, 2000), which allows the researcher to detach from his or her own world and open up to people under investigation. Some borderline cases were reread and resorted. The results of the first iteration are given in Table 3.2. Please note that the categories are preliminary since the collective transcripts were not used. Also, no hierarchical relationships between the categories had been developed. It was suggested by some phenomenographic researcher (Prosser, Trigwell, & Taylor, 1994) to start analyzing and sorting 10-15 selective interviews and then analyze each additional against and according to the categories developed with the first 10-15 transcripts. The rationale for adopting such measure was to get feedback on the study design at a national conference (Hsu, 2012) as well as to review the recruitment criteria and focus continuing recruitment efforts. I decided that at this point, I would continue recruiting in the service-learning program, while trying to recruit from the global engineering program and the undergraduate research program in order to satisfy the criteria I specified in Section 3.3.

Table 3.2 First Iteration of Categories of Description

Categories	Interdisciplinary learning means....
1A	Learning to work with others
1B	Learning to make it work
1C	Learning to recognize and utilize strength
1D	Creative integration
1E	A way to be

The additional 12 transcripts were read, analyzed, then compared against the piles accrued during the first round of analysis. At this point, no label was given to the different piles of transcripts; instead, rounds of data analysis were done focusing on a different focus each time (Akerlind & Åkerlind, 2005):

- Focus on the meaning or structural components of the categories of description (pile)
- Focus on the "how" and "what" aspects of interdisciplinary learning
- Focus on the similarities and differences between categories (piles) and between transcripts associated with particular categories (piles)
- Focus on borderline transcripts
- Focus on transcripts with certain aspects that do not fit the proposed categories of descriptions
- Focus on how removing and adding transcripts to category changes the collective account of experience

I wrote a detailed description for each pile of transcripts and went back to the analysis, creating three more iterations of the results. I then presented the categories of description detailed in Table 3.3 to three other engineering education researchers who had experiences with the methodology to make sure my interpretation of the data is defensible and justified. I prepared the categories of description, and the rest of the group asked for the basis for the particular way of writing the categories of description and how borderline transcripts fitted into categories. I also separately discussed the results with another experienced phenomenography researcher. I received the following comments:

- Focus on the value people placed in their experiences rather than the kinds of experiences. In other words, focus on the second-order interpretation of the transcripts.

- Focus on the interplay between their reflection and action. What does reflection say about their action and vice versa?

Table 3.3 Second Iteration of Categories of Description.

	Interdisciplinary learning (IDPLE) is...
2A	Communication and presentation
2B	About what non-engineering majors do
2C	About people having different styles of communication and priorities
2D	Learning skills and pieces of knowledge otherwise not accessible
2E	Interfacing with people working on other parts of the project
2F	Learning essential tool and ideas of engineering to understand a bigger picture of the project
2G	Leveraging learning with social, economical or other contextual factors
2H	Seeking experience that involves "otherness".
2I	Respect and understand differences.

I revised the outcome space based on the above guidelines and presented the revised version exhibited in Table 3.4 to the same panel of phenomenographic researchers. At this point, I was not sure how Category A, B, and C would hold up because there was only one transcript in each of them. Also, I was unsure about Category D since I generated the pile based on the lack of some quality rather than having some quality. Finally, I had question regarding Category I since the two transcripts did not show the qualitatively same way of experiencing interdisciplinary learning.

The issues were resolved in the last round of data analysis after the following progress. I found the themes of awareness and saw that Category A, B, and C fit in the space. Also, I realized that student in Category D was learning, but in a different way then I originally interpret. Finally, I revisited the two transcripts in Category I. I considered the whole transcript for each of them while keeping the second-order lens on. I realized that one of them had the same experiences as Category G and the other one Category E but expressed in a more abstract way.

After making those revisions, I tested whether the Categories E and G still held and whether the collective categories still make sense. The finalized categories of description and outcome space will be presented in Section 4.2.

Table 3.4 Third Iteration of Categories of Description

	Interdisciplinary learning as...
3A	**Misconception** Interdisciplinary learning is learning about communication, interacting with others, presentations, etc. Although learning experiences involves others, what others bring to the table is not recognized as part of interdisciplinary learning. Differences of others are invisible in the learning experience.
3B	**Control and Assertion** Interdisciplinary learning is about recognizing perspectives and goals different others bring into the picture; also, one would be aware and take into consideration of the limitations of different others' knowledge when working together. However, the extent of learning is limited to a brief survey of the other disciplines. To address challenges associated with having different goals, asserting one's opinion and getting one's voice heard is an important part of interaction in these learning situations.
3C	**Coordination** Interdisciplinary learning is about coordinating needs and priorities. Student with experiences in this category has the awareness that disciplinary differences that people bring into the learning environment can be beneficial. However, before being able to work together and benefit from the disciplinary differences that people bring to the experience, there are hurdles regarding scheduling and coordination. Efforts are made to overcome and work around different styles of communication arising from cultural background, family situations, and personal values.
3D	**Evaluating and Applying Expertise** Interdisciplinary learning is to interface between or incorporate different disciplinary component into the problem at hand. Evaluation and reflection of own and others' strength and contribution is an necessary part of the process. Differences in ideas and opinions are considered essential but challenges may arise when assimilating ideas.
3E	**Intentional Learning** Interdisciplinary learning is learning knowledge and skills that one would not have learned had one not participated in interdisciplinary learning experiences. Students whose learning experience fell in this category often still use the divide-and-conquer approach. However, the difference is that students' recognize that there is an opportunity for learning something new. The approach to learning is often using others as sources of knowledge and skills, or look for resources.

Table 3.4 Continued

3F	**Advancing Collaboration** Interdisciplinary learning is learning to be proficient in collaborative matters. Reflection and consideration on how to better communicate and work together is part of the learning. Ways to achieve that includes learning to communicate between different interdisciplinary components and learning common tools that engineers use in order to bridge between different disciplinary components.
3G	**Expansion of Perspectives** Interdisciplinary learning is about grappling with how one can approach problems from different perspectives in order to solve problems more holistically, such as but not limited to consumers' perspectives, users' perspectives, and market appeal perspectives. Specifically, wrestling with how these perspectives influence and integrate with technical and engineering perspectives is a part of the interdisciplinary learning experience.
3H	**Purposeful Engagement of Perspectives** Interdisciplinary learning is engaging differences with a purpose. Students in this category would experience problems that are "messy". Changing understanding of the purpose of the problem is to be addressed with different expertise. Understanding of the expertise needed is necessary to the management of the problem at hand. Engagement with different perspectives is considered essential.
3I	**Intellectual Openness** Interdisciplinary learning is pursuing experience and skills that aligns with personal values. Distinction is made between experiences that are academic and experiences that are important to personal growth and interest.

In summary, with regard to the three variations of data analysis Akerlind (Akerlind & Åkerlind, 2005) observed, these were the approaches that I chose to use:

- I considered the whole transcript related to a particular issue instead of selecting excerpts and quotes as representation of a certain aspect.
- I conducted individual analysis but sought feedback from a panel of advisors
- The structure of the outcome space emerged as directly as possible

3.4 Validity and Reliability

Measures need to be taken to ensure the validity and reliability of the results presented. Validity refers to how the results correspond to the phenomenon being investigated, whereas reliability refers to whether similar results would be produced under consistent conditions. I adhered to the validity and reliability checks mentioned in Akerlind's (Akerlind & Åkerlind, 2005) work when considering the process of data collection and analysis, but I have found the quality strategy framework proposed by Walther et al. (2011) for interpretive studies to be comprehensive. They propose measures of theoretical validation, procedural validation, communicative validation, pragmatic validation, and process reliability to substantiating knowledge claims.

Theoretical validation refers to the fir between the social reality under investigation and the theory produced. I used purposeful maximum variation sampling in order to capture the full extent of the phenomenon studied within the scope of the study. I also paid attention to the emergent need after initial data analysis in order to adhere to the maximum variation criteria. During data analysis, themes of expanding awareness was not looked for until the categories were stabilized, which allows for a view of "the complex nature of the interactions of the elements of the social system under investigation" (Walther et al., 2011)

Procedural validation refers to using research design to improve fit between reality and the theory generated. I kept in mind the strategies of bracketing and practice of empathy in Ashworth and Lucas' work (1998, 2000). During data collection, open-ended questions were used with emotion neutral follow up questions aiming at probing the participants' experiences rather than questions confirming any presupposition that I had. During data analysis, I used a constant comparative strategy when sorting transcripts into piles, and I considered the differences and similarities between transcripts within a pile. I considered the whole transcript when interpreting specific quotes. Also, I was deliberate to not assume that there had to be a hierarchical relationship between the categories until the last iteration of outcome space.

Communicative validation refers to co-construction of the results with the research community (Kvale, 1994; Sandberg, 2000; Walther et al., 2011). Akerlind (Akerlind & Åkerlind, 2005) pointed out that finding the right interpretation was no longer the intention, and instead, finding a defensible interpretation is the focus. I have sought feedback by attending conferences and talking at different points in time to experienced researchers in the area.

Pragmatic validation refers to whether the concepts and knowledge claims withstand exposure to reality investigated (Akerlind & Åkerlind, 2005; Sandberg, 2000; Walther et al., 2011). Prior to starting the study, I observed three engineering design teams within a program that I recruited from over the course of a semester to gain insights of team processes and the kinds of problems being worked on, which gave me some contextual knowledge to understand my participants' experience. At the same time, I did not presume that everything I knew apply to the participants. As a future project, the results of the research will be used as a theoretical basis to establish a teaching tool and an assessment tool. The application towards practice and further study will establish pragmatic validity of this study.

Lastly, process reliability refers to making the research process independent from random influences. Reliability in interpretive studies I listen to the interview recordings and double-checked the accuracy of transcripts. During data analysis, I separated notes of description and notes of interpretation.

Taking the above measures ensures the trustworthiness of the results of the study. In the next section, I examined my assumptions, preconceptions, or experiences that could have affected research decisions.

3.5 Researcher Reflexibility

When I attended university to study electrical engineering, "design", "professional competencies", or "interdisciplinary teams" were not terms included in daily discourses (except for design in circuit design perhaps). Coming to the States, I became fascinated with those terms and began to wonder what I have missed out on in my engineering education. Except for the theoretical interest in the topic, part of my motivation to engage in this topic of interdisciplinary learning was this intention to learn about others' experiences.

The second year in engineering education when I was in Dr. Robin Adams' design cognition class, we had to write a term paper titled "Design as X". I proposed the idea of exploring "design as diversity". When I came across the literature on interdisciplinary learning, I thought I could be using disciplinary affiliation as an anchor to talk about diversity.

When I started to explore the topic of interdisciplinary learning, I did a small project observing interdisciplinary teams in the service-learning program that I eventually recruited from. I sat in the team meetings of three teams, two working on problems of assistive technologies and one on education, for a semester. I tried to identify if any of the frameworks that I mentioned in Chapter 2 would be useful to understand the disciplinary aspect of the interaction. I thought I was getting superficial information. I need to get to know what the individual think and move away from observing the team as a whole. That was when I started to explore experiences of individuals and the variations of the conceptions. I did get a glimpse of the structure of the service-learning program, and I thought that would be beneficial to understand some the participants' experiences. At the same time, I was cautious about making generalized assumptions about how that would affect their perception of interdisciplinary learning.

CHAPTER 4. RESULTS

4.1 Introduction

This chapter presents the results of the study, the qualitatively different ways that students experience interdisciplinary learning. The results consist of eight categories of description based on the experiences of the 22 students interviewed for the study. The critical differences between the categories will be described in this chapter. Additionally, the categories of description form a hierarchical structure called an outcome space.

4.2 Outcome Space Overview

This section provides an overview of the eight qualitatively different ways that undergraduate engineering students experienced interdisciplinary learning. Table 4.1 provides the descriptions of the categories. The relationship between the categories emerged with the categories during data analysis. The categories along with the logical relationship among them form the outcome space. The categories vary along two axes of themes of expanding awareness, "engagement with different others" and "purpose and integration". The scales of the two axes were derived from the categories of description and are ordinal in nature. All the categories except for the first three are related to form a more comprehensive way of experiencing interdisciplinary learning. The outcome space is presented in Figure 4.1. Additionally, the critical differences between the categories are summarized in Table 4.2

Table 4.1. Categories of Description of Students' Experience of Interdisciplinary Learning

	Category Description: Interdisciplinary Learning (IDPLE) as:
A.	**No Awareness of Differences** Students focus on learning skills and strategies that help to complete tasks while working with others but show a lack of awareness of disciplinary differences and contribution.
B.	**Control and Assertion** Students experience differences as opposition to their position. Cursory understanding of other perspectives is learned in order to maintain control in the situation. At a minimum, assertion of one's voice is necessary before reaching compromises.
C.	**Coping with Differences** Differences of others are being respected and included. However, some aspects of differences become overwhelming. The goal of learning is not well-defined as students mainly cope with differences.
D.	**Navigating Creative Differences** Students value differences in that they recognize that complementary knowledge and skills are required to address the problem at hand. Although there is recognition of a common goal at the project level, there are "creative differences" regarding the details of the solution space. Interaction, specifically explanation and negotiation, leads to sense-making and convergence of perspectives for the benefit of the task.
E.	**Learning from Differences** Students recognize that differences in skill sets and knowledge enable them to learn. They credit others as a resource for learning.
F.	**Bridging Differences** Students learn strategies with which they can enhance collaboration across disciplines by noticing connections among different knowledge and skill sets.
G.	**Expanding Intellectual Boundaries** Students experience perspective-taking which broadened their mindset. They also reflect on the limit of their disciplinary knowledge. However, there is uncertainty regarding how the new perspectives relate to the existing ones.
H.	**Commitment to Holistic Perspectives** Students are committed to a more comprehensive understanding of the problem. Different perspectives are actively and purposefully engaged to address the complexity in the problem. There is consideration for creating space for disciplinary different people to interact.

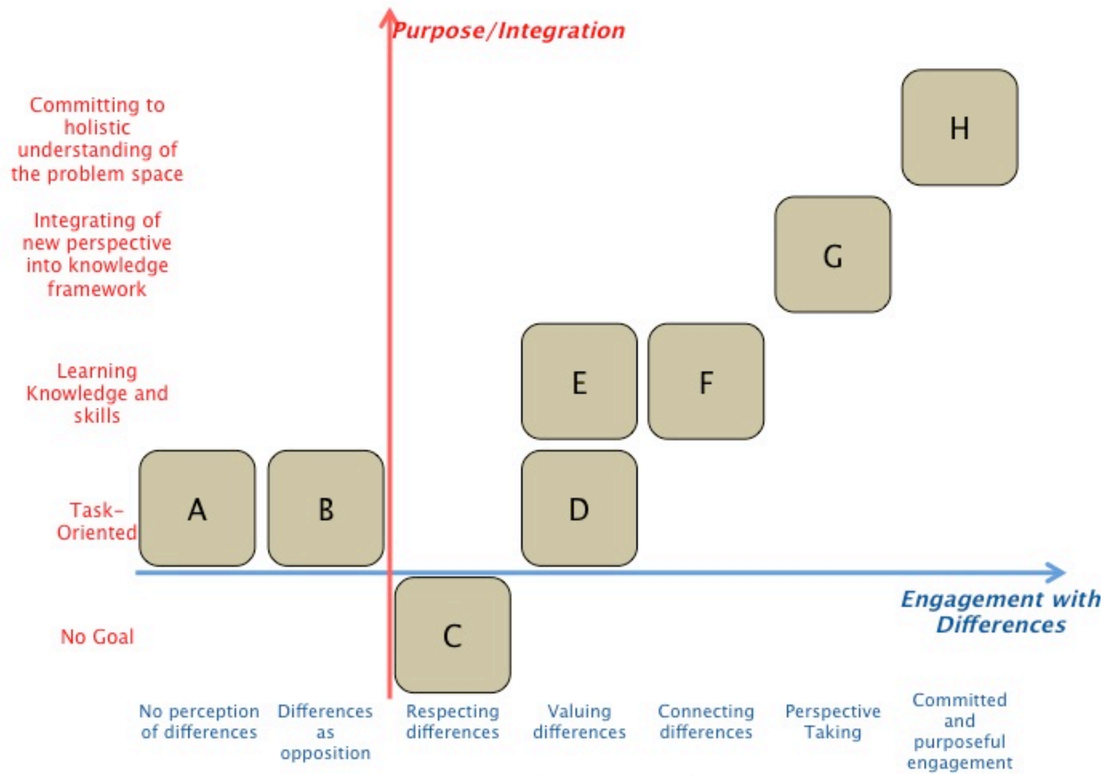

Figure 4.1 Outcome Space of Interdisciplinary Learning

Table 4.2 Critical Differences between Categories

Categories	Differences between categories
A	Engaging in tasks but having no awareness of differences of others as part of interdisciplinary learning.
B	Engaging in tasks and being aware of differences/different others in interdisciplinary learning but perceiving differences as threat to one's own goals.
C	Starting to value the differences that others bring in the learning context but staying in the space of coping with those differences instead of having a goal of learning through those experiences.
C->D	Having a goal when engaging different others: to be able to do the task well by having people with different others contribute to the team.
D->E	Going beyond merely working with differences to learning new knowledge and skills .

Table 4.2 Continued

E->F	Being reflective about collaboration and having strategies to address differences.
F->G	Beginning to question limit and boundary of old perspectives; beginning to integrate other perspectives into ways of thinking to address context related questions.
G->H	Commiting to bringing holistic perspectives to the tasks by purposefuly engaging expertise.

4.3 Categories of Description

This section provides a detailed description and demonstration of the eight categories of description of engineering students' ways of experiencing interdisciplinary learning. The categories were developed from the interview data of the 22 students who participated in this study. The transcript from each interview, including the participants' description of their experiences as well as their reflection on the experiences, were considered during analysis.

Although each transcript was analyzed as a whole, only selected portions of the transcripts are used in this section as evidences to illustrate the categories. Also, pseudonyms were given to the participants as well as the curricular program they referred to.

4.3.1 Category A: No Awareness of Differences

In Category A, interdisciplinary learning was experienced as no awareness of differences. The goal of interdisciplinary learning was to learn about general skills needed for completing projects. While these skills were essential when working with others, there was no recognition of the different skill sets that people bring. The student whose learning experience fell in this category demonstrated a lack of inclusion of different others' contributions to the scheme of interdisciplinary learning even when various others' are involved. Included in this category was the experience of Nash's.

Students' focused on strategies and skills that would help with completion of the task without awareness of the disciplinary differences and disciplinary contributions to the task. For example, Nash worked with various people with different backgrounds, including a teammate with more experience, design reviewers who offered various insights, graduate students who were available to help. However, interdisciplinary learning in his experience or understanding was merely the interaction and communication with them. Even through Nash recognized the resource that others' brought to the table, he did not include those different others as resources when asked to reiterate what interdisciplinary learning meant to him.

Apart from the technical things, there are a lot of other things, like you learn about teaming, you learn a lot about communication, [and] you learn how to interact. And one more thing: you know, there's design review twice a semester, so you get a lot of presentation skills. …. there's a lot of communication skills and, you know, how to do things in a timely manner, things like that. Not always academics. There's a lot more to learn.

In the next example, when further probed about the interdisciplinary aspect of his learning experience, Nash continued to describe his experience of interdisciplinary learning without discussing his experience working with different others.

I think it's . . . it's not just like the typical academics, like, it's not like textbooks, memorization, teaching things and you learn things and you give exams and you get grades. It's like . . . it's how learning experiences, how learning affects your practical thinking in your personal life and basically helps you as a person rather than, you know, academic. Yeah.

The last example further illustrated how the lack of awareness of the difference in the experience. Nash illustrated that his interdisciplinary learning experience taught him "soft skills", without taking the differences of others into account as reasons for needing to communicate.

Ooh, I think, we've got to learn a lot in our life. Like, it's not just like taking our core classes and passing them, because when we go to the real world after we graduate, we've got to know practical things: how to deal with people, how to communicate with people, how to present stuff, and . . . you know, things like that, how to prepare documentations. So, I think it's really important. I think it's much more important than actually learning academic textbooks, so . . . that's pretty much what I feel, in short, yeah.

In summary, there was a lack of awareness of disciplinary differences and disciplinary contributions in the interdisciplinary learning experience in this category. While the experience was task-focused regarding learning skills and strategies that helped with completion of the task, such as communication and project management, there was lack of reflection of how differences may contribute to the need to communicate or to manage project.

4.3.2 Category B: Control and Assertion

In category B, interdisciplinary learning was experienced as control and assertion. Unlike the previous category, students in this category were aware of the differences that people brought. They distinguished between working with engineering students and non-engineering students, and they link the perspective of different others to differences in problem representations and different roles they play in the tasks. Interdisciplinary learning is especially about the perspectives the non-engineering people bring. The goal of learning is to know enough about the goals and directions that non-engineers tend to proceed with, and the students considered those goals contradictory to those of the engineers. By being informed about others' intentions, one can handle these opposing goals by standing firm by one's opinion. Included in this category is the experience of Abe's.

Abe's experiences reflected considerations for what different others' knew or not knew. For instance, Abe was conscious about not using engineering jargon when working with non-engineering students.

There were different people and not everyone was from engineering, so I had to limit the technical jargon, and I had to sort of speak so that everyone understood, and not use terms and not use information that people from other majors would not use.

Nonetheless, the other perspectives posed as opposition to one's own. Abe encountered different others in his experience of working on several different class projects, some of which would be defined as engineering projects and others not. He defined interdisciplinary experience as working with people from different majors. He learned some surface information about his classmates' different fields as they relied on some of their disciplinary perspectives when tackling the task at hand.

Our final group project was, we were given ten thousand dollars in virtual money, and you had to come up with a plan for that money to improve something at [University Name]. And we did that. We went around [University Name], and we saw that a lot of the pavement and the path walks were broken, so we made up sort of a plan for . . . we had to budget the money and then give a speech on how we would go about improving the sidewalks and allocate the money. So I sort of came up with a bill of materials for that thing, and then this other guy, who was in construction management, he sort of came up with how and, like, what sort of contracts would go out to different companies and on what criteria the contracts would be based on. So I sort of learned a lot about how these things work, like construction and stuff. There was a communication major itself, so he was good at speaking, so he's the one who took charge of the whole speech and the *presentation aspect of it. And yeah, there was, I think, one other guy and he was sort of all over the place (laugh), yeah.*

Abe believed that knowing enough about the goals and directions of other non-engineers gave him an advantage regarding controlling the directions of the task.

In Abe's experience, working with non-engineers in an interdisciplinary project was more difficult than working on engineering-specific projects. The reason was that there was less that he had less control over the non-engineering aspects of the project.

I'm definitely more comfortable in working on a very engineering-specific project versus an interdisciplinary project where different opinions are needed [and] I'm not the one in control of the project, I guess. So, I mean, in engineering, I'll know what is happening and what's going to happen and I can sort of plan ahead for it and sort of control it. Even if it's a group, we all know we are on the same page as to what's happening. If it's an interdisciplinary project and it's a project—let's say the one where I did the pavement reconstruction. There, everyone was not always on the same page all the time. Maybe I had something else going on in regards to the project and someone else was working on something else in regards to the same project, so you're not on the same page.

Abe learned to listen to others' opinions, and to more importantly, voice his own opinion. It was especially important when there were differences in perceptions of the goals of the task. Learning about other discipline's possible intent made him feel in control of the situation.

It's . . . well, it's more of a learning experience that . . . I get to know how other people outside my major think, and that sort of prepares me for working as an engineer in later life when I'm going to have to deal with— suppose I work in sales. I'm going to have to deal with people who are not going to have engineering know-how, so I'm sort of preparing myself by working on these interdisciplinary projects. So it's sort of a good thing for me to be part of these projects, so that I can prepare myself and learn how to *deal with people who are not in engineering, who are not going to always think from an engineer's perspective.*

A specific difference Abe discussed was how he viewed constraints posed by other disciplines. It was necessary for him to know where these constraints might come from in order to making compelling arguments to voice his opinion.

Something I might say from an engineering point of view might not always go down well with someone who's controlling the budget, for example. [continue] He'll just see the current project and he'll say, "No, you're going to go for the cheaper option." So, that is sort of a learning thing that if you work on interdisciplinary you'll know: that not everyone is going to agree with you. Even though what you think makes sense from your point of view because you're just thinking from your point of view. [continue] I'd force my opinion (laugh). I'd argue with him. There always has to be a compromise, so I'd probably reach a compromise, depending on the situation.

In summary, the focus of the experience in this category was that student saw disciplinary differences as posing goals that might be conflicting to engineering objectives. There existed a division between "us engineers" and "others", and there potentially were conflicting goals between engineers and non-engineers. Learning just enough surface information of the other disciplines and their perspectives was imperative, since understanding was needed as one managed these different goals. The method of working with different others was to voice one's opinion to overcome an agenda not aligned with the one's needs.

4.3.3 Category C: Coping with Differences

In Category C, interdisciplinary learning was experienced as coping with differences. There was awareness of disciplinary differences and willingness to accommodate differences. However, before being able to work together and to benefit from the disciplinary differences that people brought to the experience, there were hurdles to overcome, such as issues of scheduling and communicating. These issues arose, for example, due to differences in styles of communication and time concepts arising from cultural background and family situations. Additionally, the goal of interdisciplinary learning was not well-defined as students mainly coped with different others. Included in this category is the experience of John.

Differences were valued and respected in this category. For instance, unlike the interdisciplinary learning experience in category B where other perspectives were something that poses hurdles, John recognized that differences could potentially enable learning and increase one's knowledge base.

Mmm . . . the most important aspects that I felt that I won during that time were to face . . . different . . . to face different . . . not sections, but . . . mmm . . . to face backgrounds of the work that other people have done, besides just concentrating on mine. That helped me to go a little bit out from my environment where I feel comfortable—that is the hardware part.

Despite that differences were viewed positively, they overwhelmed the learning experiences in this category. This aspect was demonstrated by John's experience as he coped with differences in people's needs, particularly scheduling needs, and their styles of communication across two different projects. Although he mentioned how people's different expertise of people expanded his horizon, coping with different needs and styles of communication of others overwhelmed his experiences. In a learning experience involving sustainable design, there were students who needed to accommodate family priorities into their routine. John and other teammate who did not have this problem responded the situation by trying to accommodate the others' schedule.

I would just point that . . . since we have a kind of similar background, the cultural thing didn't play a big aspect. But the fact that some of the people were grad students and some *of them were undergrad students was a little bit of a challenge . . . in the way that they wanted to do some things and the way that we thought that we could approach some aspects. And of course, timing for scheduling some meetings or the hours that we would be working, because us as undergrads, we don't have—well, I don't mean that all the grads have a family or have a full-time job, but in my case, both of them had a full-time job and a family, so it was difficult sometimes to meet with them. Basically, my other undergrad partner and I had to fit on their schedule. Since one of them had a family—because the other one is just married—he sometimes couldn't meet with us during the weekends, because of the family.*

In summary, in the student's interdisciplinary learning experience, although differences that others brought were seen as valuable, efforts were instead being made to manage scheduling and communication issues that arose due to family situation, communication styles, cultural differences, time concepts, etc. Also, although student displayed willingness to include others in the task, there was not a clear goal regarding why one would engage these differences.

4.3.4 Category D: Navigating Creative Differences

In category D, interdisciplinary learning was experienced as navigating creative differences. Students valued the complementary knowledge and skills that were required to address the task at hand. They recognized that they shared a common goal with different others which they worked towards while contributing their own unique set of expertise. Although there was recognition of a common goal at the project level, there existed creative differences regarding details of the solution space. Interaction, specifically explanation, negotiation, led to sense-making and convergence of perspectives in the process. They were willing to let others contribute when they understood that others' ideas were better for the goal of the task. Included in this category are the experiences of Anna and Eli.

Eli also realized that interdisciplinary learning was beyond taking assorted courses; it was about working with different people to achieve a goal.

I guess, in a way. I think it's more helpful than hurtful, definitely, now. Because it helps. it's always the same thing, to give you that broadened mind scope to see all different aspects. Before, I guess, when I was coming into it, I was like, "Oh, I'm going to be working with all these civils, and I just want to work with people—" You know, it's like the same thing like maybe like in high school when you already know you want to just do something in science or something, rather than take these liberal art classes or all these other things. But I think it's always like the same goal or answer, so that you know all these different aspects to help you.

Students worked with people with diverse skill sets to achieve a common goal. They not only respected the differences, they regarded others as valuable contributors to the tasks. Anna, who worked on designing an off-road utility vehicle with an international client, explained how diverse sets of expertise could be useful to the task and could contribute to the shared goal.

Obviously, design skills for the actual vehicle are very necessary. So anything from like how much stress is going to be on different parts of the frame to what's the best way of doing the braking system in a Third World country, which is definitely not the same as we do it here. But then you also needed people that knew about how to do 3D modeling on the computer; we had lots of that to do. There was a lot of looking up parts and prices and what they could find in Cameroon, because we tried to make what they could use there, so everything we already knew that they could use. And then there was just keeping things organized. We wrote up a business plan about it, so there were business aspects of it as well.

Although students emphasized that contributing to different aspect of the task enabled them to achieve a common goal at the project, at the task level there existed "creative differences", different ideas relating to how specific tasks could be achieved. Understanding these ideas was challenging, but it was through the process of discussion, listening, and negotiating that the students in this category worked and learned. For example, Eli illustrated how he accommodated a teammate's idea on a detail he initially ignored when working on a rain barrel system.

I guess, learning to be more adaptable with people, because different engineers think in different ways. Like, I designed the barrel in a different way, and then they came to me, they were like, "That's not the way we want it, that's not going to work," or something like that. I'm like, "OK, I'll do it this way, then. I'll do it this way." And it's to see how people, like different engineers, the way they think and stuff, and how you can accommodate people's needs to, I guess, deliver the same goal, because everyone has different ideas from those engineers.

Eli further provided an example of the idea his teammate proposed, and how he negotiated understanding, and finally how he came to terms with it considering the goals of the project.

So I couldn't do it like this because what they wanted to do is have a filter, or some kind of filter mesh, before the water entered. And I thought—I mean, I thought it would just be OK to just do it like this, if the user, whoever buys the barrel, can filter the water their own way. But they were like, "No. If you're going to make the rain barrel, you have to make another mesh on top." So then I just went back and just re-designed it again, so the water could be filtered, and then the user can use it for their gardens and whatnot and stuff like that. I didn't even know it was going to be drinkable, too, yeah.

Similarly, Anna had the experience of frustration when people presented very different ideas, but she did not dismiss those ideas and realized their virtues. Although trying to negotiate understanding could be an uncomfortable experience, students who experienced interdisciplinary learning like Anna ultimately had the goal of the task in mind; that is, if different others' ideas fitted better with the task, the students were willing to let the others contribute instead of insisting on their own ideas.

Well, sometimes it's just frustrating because there are so many of them. But also it can be frustrating because they aren't what you would think of, and so . . . I think of an idea and I'm like, "Oh, this makes sense to me." And maybe it's not the best idea, but it makes sense to me, so of course that's what I want to do. And so I have to have the other people explain their idea and, like, then try to figure out which actually is better for the solution.

In summary, students recognized the benefits of having a people with diverse expertise on board in an interdisciplinary task. They pitched in using their own strength while letting others contribute. They navigated the creative differences among different others while holding the benefit of the task in mind.

4.3.5 Category E: Learning from Differences

In Category E, interdisciplinary learning was experienced as learning from differences. Students focused on learning new knowledge or skills, specifically, through interacting with different others. Students valued the differences in skill sets that others bring into the setting, and they credited others as a valid resource for learning. There are variations within this category regarding students' agency and motivation to learn. For some, learning is perceived as a coincidental consequence of interacting with different others; while for some others, they strategically learned what is necessary for the task at hand. In both cases, these newly learned knowledge and skills had some significance to the students personally. Included in the former is the experience of Kelly, Jules, Ash, Adrian, Henry, and Mark.

Students in this category learned skills or knowledge they considered unattainable in a non-interdisciplinary learning situation through interacting with different others. For some of the students, learning was seemed more as coincidental result of interaction. For instance, Jules learned about woodwork skills in a service-learning project designing soapbox derby cars for children with special needs, which was unrelated to her own major of acoustic engineering. She was able to learn from others who had more experience or expertise.

Um, well, the fact that there were a lot of different majors involved and it wasn't something that was particularly connected to my major. Although I like what I'm doing in my major, it's a good change, you know, to be able to learn something else and then, um, see how . . . yeah (laugh). Like, um, you know, building cars, you need to learn about materials, you need to learn about . . . basically fixing the little car and, um . . . the best way to cut out those—what's it called?—wood. Yes, cut the wood to make it more stable and, you know, the shape of it.

Skill-learning in Jule's experience was perceived more as an accidental coincidence of interacting with different others. For her personally, she was able to reflect on her experiences from observing how she and others learned.

It kind of gives me an interest into things. Because I also have friends who are taking similar courses in different majors. So when I talk to them, you know, it kinda gives perspective on like, "Oh, I'm learning this, and this is how I learned it," but they learned it a different way, you know. Because I have a different style of learning than my friends—you know, different people have different styles—so I guess . . . the practical kind of learning suits me more.

Similarly, interdisciplinary experience allowed Ash to learn about motors in another service-learning project designing a door-opening device for disabled stakeholders, which she considered something she would not have learned if she was not in an interdisciplinary learning experience.

Well, I learned something about motors: the torque. Like, OK, if it gives this certain amount of torque, you could turn the knob. Thinking of it as a normal layman, I know that you need so much power, like you need more power to do something and less power to turn a button on or something, but I didn't know the exact stuff that goes on, like the shaft and all that stuff. So, from that experience, I learned something new. I didn't know about circuits so much, like just one on/off button would have a huge circuit, but, you know, sometimes it's really small ones. And I didn't know about soldering, so I learned that also. Many small things I learned, but overall, it was a good learning experience.

For Ash, she regarded an interdisciplinary experience as another opportunity to learn, not different from non-interdisciplinary experiences, except for discrete knowledge and skills from other disciplines.

Well, see, I think interdisciplinary is very valuable because you will learn stuff from their discipline also, whereas if I have a person from the same team, I'm going to be learning all that stuff later on also in my courses. I mean, I'm going to learn it, but knowing it earlier is a good thing. Like if me and my partner we are from the same department, he can tell me what I should expect or, you know, "This is some problem I faced, and that's how I solved it," so you know if you ever come across something like that, you have a solution to how to solve that problem. But if you're in an interdisciplinary team, you get to know things from other disciplines. Like I had an electrical engineering partner, that's how I got to know about soldering. Even though they are small things, it still makes a difference, you know something more. So I wouldn't say that it's just being a team; it depends on the kind of team it is.

In contrast to Jule and Ash's coincidental encounter with the opportunity to learn something different, learning could be more strategic when students recognized some amount of learning is required to finish tasks at hand. Kelly demonstrated how she learned about designing a parking lot as a necessity of the project rather than just something new she encountered.

And so while I was designing this parking lot, I was having to think about like the strain of the cars on the asphalt and like all the different runoff options, and so I was able to kinda use that design process that I'd learned in my engineering classes to work through the problem, but I haven't like, um . . . like, I've never taken a class about asphalt, which I know that a lot of, like, civils take a class about concrete or something. I've never done stuff like that, so we were able to use like . . . you know, ask different professors who are familiar with that material for help on our project, and our advisor would connect us with different people. One of the people who I worked really closely with is the president of the Asphalt Pavement Association of Indiana. My focus is, you know, natural resources within agricultural—so soil and water—and I was working with concrete. It was interesting to get to use those different tools.

Likewise, Adrian learned concepts and skills needed to conduct an interdisciplinary research project of creating nano-fluid. The concept was not familiar to him, so he had acquired information from different resources. He was able to attain new knowledge and skills from his independent studies as well as from mentor guidance.

It's more interdisciplinary because I've been exposed to several aspects of engineering. With electrical engineering, for the electronics portion of the project, to create the square wave signal to disturb the fluid stream, and then you also have to use a little bit of mechanical engineering in pumping the fluid through the droplet generator. There's also chemical engineering, when I was learning how to actually create the solutions of the nanofluids. And then, I'm also an aero student, so I have a good background in aerospace engineering. I learned a lot from, like, reading my mentor's dissertation for his PhD, I learned a lot about chemical properties, and also reading papers off, like, *Google Scholar. I read a lot of papers and learned that the field goes, like, in so much more depth than I ever knew. And then, being exposed to the new equipment that I hadn't used, that they deal with, like, in their specific fields.*

Mark's learning experiences told a similar story of learning what was needed to complete a task of constructing electric race vehicles in a collaborative project between the engineering and the technology college.

I looked up some of the other races that are conducted throughout the world, made some general rules, and then from there, we kinda built it, designed it, prototyped it, kinda tested it, and the biggest portion was testing, to see what were some of the flaws in our initial, I guess, hypotheses. And we found that, you know, there's a lot of torque through electric motors—that's one of the biggest things—and so we had to gear up some of the protective restrictions around the motor, things like that, and then we just learned from there. You know, we need battery protection because if there's a collision, we need rollover protection; these all came through just testing. And then, after the first event, we realized, "Well, people can't use the batteries too much, or they burst into flames," things like that. We learned through events that new things needed to be changed, so it was kind of like a learning experience.

The same goes for Henry when he engaged in an interdisciplinary learning experience working on building a seismic simulator.

One more interdisciplinary thing that I learned was CAD modeling. Electrical engineers don't have to take CAD modeling, and I didn't know CAD modeling before I did [service-learning program], so I kinda learned. You know how they have skill sessions? So I learned CAD modeling through it, and it helped me a lot, actually, in the research I am doing. I was doing it last semester, too, and it helped me kind of, you know, present the model of what I was making. So CAD modeling helped me that way.

Regardless of whether learning was coincidental or more intentional to the students, students credited the others with different knowledge or skill sets as a credible source of information and valuable resources for learning, as illustrated by the above and the following examples. For instance, Kelly had just finished freshmen engineering courses at that point, and she recognized that she needed to acquire other knowledge related to the project. She learned from teammates who were more experienced and knowledgeable in the process.

My teammates who were doing the drainage ditches, they worked on picking plants that would . . . you know, the root system would keep the walls of that from eroding. But they had to ask a lot—well, I mean, not ask a lot, but they did a lot of research into like the grade of soil that would be eroding, and they had to do soil samples, and they worked a lot with professors over in the soil research facility. And, you know, they're going into construction engineering and industrial engineering, and they're into looking into plants and planting things in soil. So I know that our roles were kind of reversed, but it worked out just as well because we all . . . like, a bunch of us were pretty young, so we've mostly had like the design process and the basics and stuff like that, and then we were just able to . . . you know, we could figure out who we needed to ask for help in our other areas.

Similarly, through consulting experienced others, Ash was able to overcome the roadblocks she encountered in her projects.

They were working on another project in the same group. They were designing a GPS device, so they were both working on that. But at the same time, they were advising us. So if we were at a roadblock, then we would go to the other [people]. They were also a CE-and-EE combination, but the CE guy was doing all the programming and stuff, and they would tell us what to do next. If we hit a roadblock like, "OK, we don't know what to do now," then we would go to them and they would tell us.

In summary, the students whose interdisciplinary learning experiences constituted this category not only interacted with different others, but also learned from and with them to gain new skills and knowledge that they either encountered on the task or that were necessary to finish the task. Others were credited as credible resources to learn from.

4.3.6 Category F: Bridging Differences

In category F, interdisciplinary learning was experienced as bridging differences. Students whose learning experience comprised this category addressed the ways with which they could enhance collaboration through learning. They deliberately considered and reflected on issues of collaboration, particularly through paying attention to intersecting connections between different components of the task. Ways that students enhanced collaboration included addressing the commonness of the engineering experience, communicating about overlapping connection between different parts of the problem, and formalizing representation of a problem across components. Included in this category is the experience of Mo, Alice, and Brett.

For example, one of the ways that students learned to address collaboration was to emphasize the commonness of the engineering experience. Students observed that there were common tools and skills that could help them in working with others who were working on a separate component in the project. Finding commonness was used as a way to establish grounding of the problems and solution as it provided a language to talk to people who used a different kind of formalization and representation. For example, Mo saw himself as the bridge between various components that were being worked on by different people. As a project leader on designing an earthquake simulating table with two disciplinary components, mechanical and computer engineering, Mo needed to learn skills in order to be the bridge between those different components. He learned a programming language to be able to communicate with people working on the programmable components.

And, being the team leader, I had to make sure that both of the things get done on time and properly, so we had to divide the team into two teams: one would take care of the mechanical side, and one would take care of the electrical side. Of course I understood what the mechanical side was doing, but I had no idea what the computer engineers were doing. But to keep up with them, to understand what they were doing, I had to, myself, learn a bit of C computer language and try to understand what was going on so I know where they are at at different points of time, and so I can tell them how to approach this problem and how to progress. So that was challenging at first because I've never learned C language before and I had to go through all the basics. So, again, if engineering education was such that all engineers were taught these basics, then I would not have had to go through this process of learning in that class, this challenge wouldn't have been there.

Mo further illustrated that knowing some basic knowledge and formalism was a way to be able to communicate effectively across various engineering disciplines.

I mean, again, it gave me, as I said before, this perspective that for most of the projects you have to . . . different engineering fields do come together to get that project done, and communication between those different fields is very important, and that's why engineers should have knowledge of all different fields, at least basic knowledge, so that they know what their team is doing and so that they can communicate better with them. Again, having had that experience, I feel myself lucky that I understand that now as an engineer.

In Mo's experience, not knowing the tools that the other subgroup was using hindered collaboration.

Related to the project, because we didn't actually know computer language and they didn't know much about our stuff, it was very little communication regarding the project.

Yeah, as the team leader, I had to because I had to understand what was going on there. But I'm talking the teams within themselves. Be that bridge. So that's why I had to kind of have some knowledge of what was going on there.

Brett also observed that there were common methods and tools among different engineering disciplines, but he did not discuss how knowing those methods and tools can help with working in an interdisciplinary learning environment.

You know, I used to see the different disciplines as totally separate, you know. But after doing this interdisciplinary kind of work, I would say that they overlap in a lot of areas, you know. Because every engineer is going to have to do a bit of software coding; to what extent is the question. Every engineer is going to have to analyze how their solution can fail, you know. So there are a lot of central ideas to engineering, despite your discipline.

Instead, Brett focused on crystalizing specifications of overlapping elements among components of the task and communicating them throughout the duration of the projects.

I'll definitely try to put the specifications for my part, what I need and—I mean, I guess the specifications from other people that I need and the specifications that my project must have that they need, you know, and vice versa. So I would probably try to, I guess, itemize that or formalize that so that it's very easy; they can look at this and say, "He definitely needs this or this or this," you know, instead of "Oh, maybe he needs this, maybe not," you know.

While communicating specification was a great tool for interfacing between different components, here was still uncertainty that needed to be addressed along the way. Brett also considered using prototypes as a tool for communicating his end of the specifications way before the deadline.

You know, there are probably some things with the electrical aspect I would have done differently. You know, I have to provide specifications to the mechanical engineers so *that they can make the housing, you know, and I didn't make concrete specifications. You know, I wasn't really sure which wire was going to go where or what, you know, and the housing came up with a couple extra holes and stuff like that, you know, and it kinda seems like we slapped stuff together at the last minute sometimes. So I would definitely plan better and maybe have a prototype before we actually put the whole thing together.*

Sharing formalism of problem representation to target overlapping connections was another way to address the collaborative efficiency between diverse peers. Communication and interaction between different members ensured cognitive congruence among them. For instance, Alice was working on a service-learning project on designing ways to teach mathematics to middle school students. It was important for Alice to be able to communicate intersecting connections to the other members working on the task.

I kind of saw how the overlapping connections are the most important, because it didn't matter how well I had done my material analysis if I couldn't relay it to the people inputting it in the CAD program. Because if I couldn't tell them the exact dimensions, or what we needed to be getting out of it so that it would be strong enough to withstand a drop from three feet, then they couldn't design the program to allow for those factors. So, it just kind of really cemented for me the importance of intercollaboration and communicating things not only at the beginning and the end of the design process, but continually throughout it, so that you can cut back on the number of iterations you have to do to fix things that had already been addressed but just not . . . well communicated.

In summary, students whose experience constituted this category had learned strategies to improve collaboration among disciplinary components of the task. They took note of the importance of overlapping connections between these components, and they developed strategies such as information sharing as well as learning common knowledge and tools in order to bridge the differences.

4.3.7 Category G: Expanding Intellectual Boundaries

Students' interdisciplinary learning was experienced as expanding intellectual boundaries with the understanding of alternative perspectives. They started to reflect on the limitation of their disciplinary knowledge and to consider other perspectives as they realized that the complexity of the task might have to be addressed with other perspectives. However, there was still uncertainty about how the newly gained perspectives related with the old. Included in this category is the experience of Jasmin, Bri, Marna, Helen, Mick, and Mandy.

In Bri's learning experience in user-centered design course that required her and her teammate to incorporate users' perspectives and other considerations into their engineering design, which went beyond what she used to consider as engineering.

Also, doing the design but focusing on the people I think is bringing in a different aspect of design work, and so that's kind of why I think of it as interdisciplinary. And then we do use our engineering expertise when we're thinking about, OK, what would the requirements of this product be? What price range do we think is acceptable? What technologies would we think would be involved in our product? So I think that whole process made it interdisciplinary.

Furthermore, Bri was able to learn about the stakeholders' perspective by observing and talking to para-athletes. The experience has taught her to look beyond technical consideration and think about other factors that might affect the design.

It ended up not being specifically related to sports, and could be extended over the wheelchair community, but through the process and getting to know the people that were involved in sports, we felt like this could really speak to a lot of their needs. I think that process was very interdisciplinary, I guess heavily design-focused, but then we did have to think about some of the real engineering components that would go into a design, to kind of choose the best one and good economics. Like, we had to make a requirements *table for that product, so thinking about all those issues before we presented our final idea.*

The process of getting user feedback in Bri's experience was itself interdisciplinary since the users brought in a very different perspective into the design process.

It was interesting: A lot of our users ended up being computer or engineer-related, probably because a lot of them can't use their legs at all, so a sitting job. But some of the other people, like, people that volunteer in homeless shelters, that may be their full-time job, or they may have other jobs. And some groups worked with . . . what did other people work with? Some people worked with people that are DJs, whether professional or amateur, so just talking to them. And most of the people we interacted with weren't necessarily engineers, so they definitely bring in another piece of interdisciplinary because they're looking at this from just their everyday background. And to some extent, we were including them in our design process, so I think that adds another element of the interdisciplinary feel.

Mandy's summer internship working as an engineer at a product design firm brought her a glimpse of the integrating perspective of consumer understanding and industrial design with engineering design.

Like, a lot of the things we learn in class are like the upstream technology stuff, but then I had never really thought about like what a product needs to be able to be put on the shelf. Because it's not PhD chemists who are buying it; it's moms with little kids who don't care what the chemistry is; they care about like, will this keep me from getting sunburned? So I learned a lot more about market research and the business model, and who is the consumer we're advertising this to, and what are the advertisements going to say and, um . . . kind of like . . . not dumbing it down, but making it consumer . . . like just everyday things, not like all of the technical jargon, like not all the sciency stuff, but kind *of translating that—because that's important, but translating that into, why is this is a good product, in a message that everyone can understand.*

Helen had an intensive experience learning about the topic of sustainability. The learning experience comprised of seminars, discussions, and final projects to address sustainability issues on campus. Learning about sustainability allowed Helen to view problems from a broader perspective.

Um, well, it involved energy, it involved transportation, it involved different political aspects, I guess, because we were able to see different . . . like the energy company, when we went to see it, we got to talk about how industry really influences—I mean, I know industry isn't necessarily politics, but it's sort of . . . just, I guess, economical, so I guess economic reasons and all of that. Psychologically, too, and how we could maybe get people to eat less in the dining courts, because we talked about food waste and like—so we pulled from, like, everywhere trying to find solutions. Any major could go into that class, so we had so many different points of views.

As compared to prior categories which student identified a single common goal in the task, students whose experiences formed this category started to realize that the goals might not be as well defined due to the complexity of problems. For example, in Mick's experience in a global design project, after working on the design for a wastewater treatment unit, the team discovered that the community had already been using different water saving techniques. Failure to communicate with the stakeholder as well as not recognizing the importance of such communication contributed to the initial failure of the project.

We didn't have as much contact with them as we had thought we did. There was kinda like a breakdown in communication on the other end that we didn't realize happened. So it really reinforced to me that we have to keep the stakeholders, and talk to them directly, and make sure that they're thoroughly involved in all steps, because a lot of the project *could have been done a lot better had we kept in better contact and known that there was better contact with them. So that was the biggest thing, I think.*

After the unsuccessful experience, Mick realized that knowledge about the community and the user was extremely crucial. He went on to take a class in anthropology that focused on learning about community and user perspectives.

The anthropologists have been trained to work with communities, to understand the communities, to realize what's important and, um, like if something is going to be successful in a community or not. And so then they're going to be evaluating the design and working with the engineers to make sure that the design will actually be effective and not a total failure even if the design is right.

The experience of working with anthropologists cemented for Mick the importance of incorporating perspectives beyond how he used to think about problem solving.

And it also includes the human element, as opposed to just like "Here's a problem; here's the solution we're going to give them." It involves the community, involves people. It's (laugh) a very different way of thinking about it, but I think it's a very good way of thinking about it, too.

Marni also became aware of the alternate ways of approaching problems. She transferred from mechanical to interdisciplinary engineering program to be able to look at problems from other than the pure mechanical point of view.

There are, I think, almost no classes, other than electives, that you can take outside of the mechanical engineering department, which makes sense because it's a focus. However, there's very little emphasis put on environmental impact. For instance, if you design a turbine that gives this sort of an output, that's great, but at what cost? It's not necessarily something that they're prioritizing when teaching certain classes. For that reason, I found out that all of my classes could transfer over, I could graduate on time, and I could still take different classes and analyze different aspects of building that *turbine and getting a good output that's not going to cloud up the environment, I suppose (laugh).*

Interdisciplinary learning situations allowed Marni to view problems from a perspective with values that aligned with her own.

It's more open-ended, and you can look at it from different points of view. For instance, looking from a civil point of view on a class that's focused on environmental engineering, you could kind of see what the output is and not really be too worried about how fast it's going or how much power it gives out; it's more about how can you make it so that it's not quite so dirty?

Understanding of alternative perspectives due to complexity of the situation was Jasmin's experience as well as she worked on designing a utility vehicle for stakeholder in Central Africa. She characterized only the last leg of her experience as interdisciplinary. In preparation for their trip to implement the design, they started to get in touch with people with expertise in stakeholder perspectives, and the experience opened her eye to considering engineering feasibility from a different standpoint.

You know, I'd always thought of the project from a strictly engineering standpoint, you know, the design of the vehicle. I mean, yes, you think about the feasibility in a different environment but you think of it from purely engineering standpoints—you know, the cost, the materials available, etc. Whereas after talking with the anthropology experts, people who had lived there for years and years, you get more of a feel for the entire impact of the project. I think it helped a lot, especially when I went to Cameroon, having that background information, knowing what people were doing; and then when we were actually building the vehicle, you were able to kinda grasp the implications of the design we were coming up with a little bit better.

Jasmin referred to her earlier experience of taking a course on focusing on community perspective in engineering design process. Even though the topic of incorporating holistic perspective was covered in her earlier course work, the importance did not registered with her until she saw the impact for the community partners she designed for.

To me, that's hard to put a finger on, to be perfectly honest. I mean, the whole experience changed me a lot, but from an engineering perspective, I'm not sure—I mean, it was a good experience to remember to think outside of just the pure engineering behind the design. Regardless of whether or not you're designing for Cameroon or, you know, just a regular thing, um . . . looking at the whole picture. This whole project has been a really good lesson in looking at the whole picture. You know, yes, you're designing something, but you have to look at what you're designing for. And they teach you that in engineering, that's nothing new, but you don't really take it seriously—at least I didn't really fully take it seriously, and understand the implications of it, until I got extensive experience on the BUV experience.

The interdisciplinary learning experience solidified for the students the importance of a more comprehensive perspective when grappling with complex problems. They realized problem solving was beyond optimizing technical metric. However, they were uncertain of this new perspective. For example, Bri felt that incorporating interdisciplinary perspectives meant that technical work was no longer a priority. She was still negotiating how her perspectives could be incorporated into her engineering work.

I kinda feel like interdisciplinary work right now seems to be . . . It'll probably be different when I'm actually in industry, but right now it seems like sometimes you leave some of your technical expertise and work on more . . . I think the methods you use are really work well in the interdisciplinary aspect, and then if there's a need for your technical expertise on whatever project you're working on, I feel like that's when they come in. I guess my current view that will probably change later is that some of your specific techniques in your major, or your concentration, may not necessarily be used as *much—that's my current experience, at least—but the general skills that you have can be used in a different, kind of broader context, and your strengths and weaknesses that you've learned from your major can be used in, like, a broader way, yeah.*

Similar to Bri, Mandy was coming to grips of with how the different perspectives could be balanced. In here experience, it was difficult to convey the goals from very different perspectives that she had to work with.

Like, sometimes we delivered one product concept and kind of explained the three sides of it, and then sometimes we just helped the company think about those three sides of their product in new ways. So, the times when they all had to come together, it was a little harder to communicate the whole message, because it always felt like a little unbalanced. Like if it was really consumer-friendly and really appealing and you could imagine a really great commercial for it, the technology wasn't really that exciting; it was kind of what they already had, it was just like dressing up the message about it. So it was hard to balance those three out, I think, but the companies usually hadn't thought about all three things together at the same time, so . . . And almost always, they were really happy with it, even if it felt a little unbalanced. Because typically at the company, you're not working with someone who—you're usually working with the scientist or the marketing people but not someone who understands all three aspects.

Although Helen had an experience immersing in the perspective of sustainability, she could not see how the latitude related to her other engineering work.

I'm learning this material because I decided I wanted to learn this material. It was more so just an experience to broaden my horizons and to give myself those new perspectives and new experiences and just sort of make myself a more well-rounded person so that I would have the competency and knowledge to be able to tackle things in life better, honestly, because I don't think that any of that really applies to what I'm doing in class (laugh)—and what I'm here to learn at the university.

Moreover, Helen was not as open-minded towards working with other perspectives when working on a research project later.

Like, I know that we all have different topics and everything, and I do talk to people in my lab who are doing something completely different from me, who have non-engineering majors, and I don't have to, like, open my mind up as much to talk to them about their sort of thing as I did in order to work on that project with those people, because it was just . . . there are, like, parts of your mind that you sort of close off when you're looking at a problem, because they're not the ones that you're most comfortable with; and sometimes, exploring those things, you realize that you actually know more about them than you think, but you focus where your strengths are. And sometimes, it's not necessarily that those other things are weaknesses; they're just not as strong as something else that you're in. So it was nice to be able to open up . . . mentally, intellectually (laugh).

The disparity in Helen's experiences was perhaps due to how she classified her learning experiences: as something "just academic" versus something more transformative.

I think of two different skills sets: There are the skills you learn in order to do your job or whatever you want to do with your life academically, and then there are the skill sets you learn that you want to have for living life and being able to socialize properly and being able to be like an active citizen and just be a good person. Like being a good human being versus being good academically.

As for Jasmin, she grappled with what it meant to be designing for local communities after she witnessed the importance of community perspective in her global experience.

Just understanding the culture and what you need to design for, which . . . people forget about when you step outside of an environment that—you know, even United States, Europe areas, it's similar sorts of cultures. But when you step into a completely different *culture, they have different expectations of what the product needs to be, um . . . that side of things. It's not . . . it's not engineering, but it is at the same—it's a side of looking at the product design that you really don't think about because most people don't consider in engineering.*

In summary, interdisciplinary learning was experienced as understanding from alternate perspectives, but there was still uncertainty related to approaching problems with those new perspectives, as well as how those new perspectives related with the old.

4.3.8 Category H: Commitment to Holistic Perspectives

In category H, interdisciplinary learning was experienced as commitment to holistic perspectives. Students believed that different perspectives were necessary to understand the breadth and depth of complex problems. They also had strategies to purposefully engage different perspectives, including knowing whom to engage and how people with different expertise might interact with each other. Included in this category is the experience of Trey and Saylor.

Students whose experience comprised of this category were committed to a holistic understanding of the problem, which was evident in Saylor's empathy for the users she designed for as she managed and designed for a company that built healthcare facilities. Her commitment to user perspectives was evident in how she assessed the quality of her work beyond what was required by regulation to what would mean to the users.

And I think that there are certain things that are just standards, that absolutely by law and by policies have to be done. But there are other things that just have to do with being considerate (laugh), you know, and making sure that you're worried first and foremost about the comfort and the efficiency of the system that's already working, and making sure that you're doing the best job you can, while being as invisible as possible *(laugh), and as visible as you can, too. So I think it's just really valuable in that it's kind of constantly reminding me that yes, my goal is to build this and this, but my goal is really to build this and this for a set of users that eventually are going to come and use this system, or might be using a system alongside what I'm building. And I think that that really makes a difference in how you view the quality of the work you're doing, how you view the kind of decisions that you make day-to-day about . . . that, you know, could easily kind of be like, "Well, I can make more money this way or that way," or "This will be easier," or "This will be . . . whatever, you know, thing that sounds beneficial (laugh)." But at the end of the day, it's all about what that end product is going to be for the users. And I think that that's a really cool thing to always remind yourself of, especially because when you're trying to complete an engineering degree in four years, you don't have a lot of time to really learn anything about humanities (laugh), to really learn anything about what our users are doing and why.*

Students' commitment to a more comprehensive understanding of the problem could was also revealed by their purposeful engagement with different others. For instance, they intentionally sought out different others with appropriate expertise in order to address the complexity of the problem. Saylor's commitment to the users was exhibited by her attentiveness to continual community involvement in another experience of designing and building a community center in a global engineering project. At the beginning of the project, she and her teammate learned very quickly that only considering engineering metrics would not be adequate for the complexity of the problem at hand. Therefore, they purposefully engaged with an expert to ensure they fully considered community perspectives.

When we first approached the project, we were kind of looking at it as engineers. They want to build a library and community center there, so from my standpoint, the first thing is like, you know, we're just kind of thinking about all the practical things: where's the *money going to come from, and who's going to build it, and how much time do we have, and those basic questions that you're asking yourself when you go into any kind of construction standpoint. But, we quickly started to realize that those were not all the questions that we needed to ask. So, from the beginning, we actually included a linguistics professor into all of our discussions, who also has done a lot of work trying to revitalize languages in Nicaragua. So she's very familiar with working with these difference communities, and the kind of things to look for to make sure that it becomes a collaboration as opposed to just going somewhere and performing an act that doesn't really help them in the long term, that doesn't just kind of leave a building there (laugh), you know, and leaves them without any further education or further knowledge of what exactly happened, and making sure that the community is actually invested in what we're doing there and invested in our presence there.*

Purposeful engagement with different perspectives was also revealed by Saylor's process of considering whom to engage and where to find appropriate expertise.

I think that that's . . . kind of like what I described is like that first step [asking the right kind of question to frame the problem]. But once you get to that point of realizing, yes, OK, you're not just the engineer. But at the same point, you're right, you still . . . just because you realize, all right, I'm not only an engineer, doesn't make you a linguist, doesn't make you anything else. It doesn't make you an anthropologist. So it is about recognizing that and then saying, "OK, who does have all the knowhow about this? Who can give me that information? Where can I look for those better questions? Who could help me, you know, give me this broader view?"

Not only did Saylor seek out people with different expertise, she also was also conscientious about the kinds of interaction between people from very different disciplinary cultures.

I guess it's just how we're all taught to approach problems is very different, and how things get done in different settings is extremely different. I think when you try to sit down a group of engineers, things are very [much like], "OK, you need to do this part, and I'm going to do that part, and it's all going to come back together." And I think that in other . . . like in some liberal arts settings, it's a little bit more collaborative from the beginning, or it's just sort of like, "Well, you do the work, and then I'll critique the work." You know? I mean, it's just—even subtle things, it's just very different. And I think that getting everybody on the same page, getting everybody to agree on just a way to approach the problem, is difficult, and then, getting people to communicate, because we just—we speak different languages (laugh).

Moreover, Saylor was deliberate in creating an environment in which people speaking very different disciplinary languages can start a meaningful conversation in order to share knowledge and create solutions.

Like when somebody is talking about something they really know, and they're expecting you—even if they don't actually expect you to know what they're saying. But you're not going to feel comfortable asking them what they're talking about (laugh), you know, because you're just going to nod along and say OK. So I think just that kind of sitting down and being able to say like, "This is a place to ask questions. This is a place where we recognize that we don't all know the same things." It's not necessarily a hard conversation to have, but I think that it's a conversation that's often not had, and kind of a step that's ignored. That makes it really difficult, and is why a lot of teams, I think, fail when they try to do this work: because they come from these different worlds, and they don't really match up.

Similarly, Trey paid particular attention to the expertise people bring and the likely interaction between them.

So if I have a senior in ME who's never had any interdisciplinary experience before, I need to find how he's going to fit in this puzzle piece, and I need to find out how people are going to interact with him, how they're going to share their experience with him, and how they're going to get feedback from him. So I need to make sure that I understand—and over these last couple years, it's really helped me understand . . . to my own ears, I think I'm getting a better handle of what it means to be a mechanical engineering student or to be another type of engineering student or—again, I'm just breaching into this territory, but—to be a humanities major or to be a business major or something. And once I understand this, then I'm much more open to the idea of bringing these people in. And because I have an intimate knowledge of the project itself, maybe not the mechanics of it—you know, certainly I don't have the background to say whether or not this turbine is as efficient as it could be—but to understand the nature of the project. I don't know that there's anybody who could provide more of that insight, and so therefore, I'm probably the most qualified to say, "Well, I think you can fit best here," or "Oh, you're an anthropology major? Well, you're going to join me on this meeting with the project partner because I think you're going to have some really invaluable input."

Trey also anticipated the differences in thinking and working that a person that is different from him would bring to the project.

I would say it means collaborating with people in areas that I have little to no knowledge of. I would say that it means listening a lot. That you take input from people who are able to offer things that maybe you've never heard of or hear perspectives from people that are unfamiliar to you. So, moving forward, I would like to see input from majors that I've never encountered before, purely because I know that from their education, they're going to have a much different timeline than I ever had or that even anybody on my project currently has.

In summary, students whose experience comprised this category were committed to holistic understanding of the problem and bringing in interdisciplinary expertise to address the complexity of the problem. They learned where and how to seek those expertise, and were intentional and active in enlisting them in the project. They are considerate and conscious of the kinds of interaction that might occur among groups of people from different worlds of expertise.

4.4 Category Differences and Hierarchy

The hierarchical structure exhibited in the outcome space was based on the critical differences between the categories. The order of the hierarchy reflected a more comprehensive way of experiencing and understanding interdisciplinary learning as revealed by the transcripts. There would be aspects of the less comprehnsive categories in the more comprehensive ones.

The eight categories of descriptions were related along two axis of themes of expanding awareness, *purpose and integration* and *engagement with others*. Five of the eight categories, Category D though G, represented a structure of more comprehensive ways of experiencing interdisciplinary learning. While still logically related to the other categories through the two axis, Category A, B, and C were stand-alone categories. Category A and B represented a lack of positive engagement with different others, and Category C represented a lack of goal and integration in interdisciplinary learning. Threshold concepts seperated Category A, B, C and the rest of the categories. Figure 4.2 illustrates the relationship between the different categories. The description of the critical differences between the different categories was summerized earlier in Table 4.2 and will be described in detail in this section.

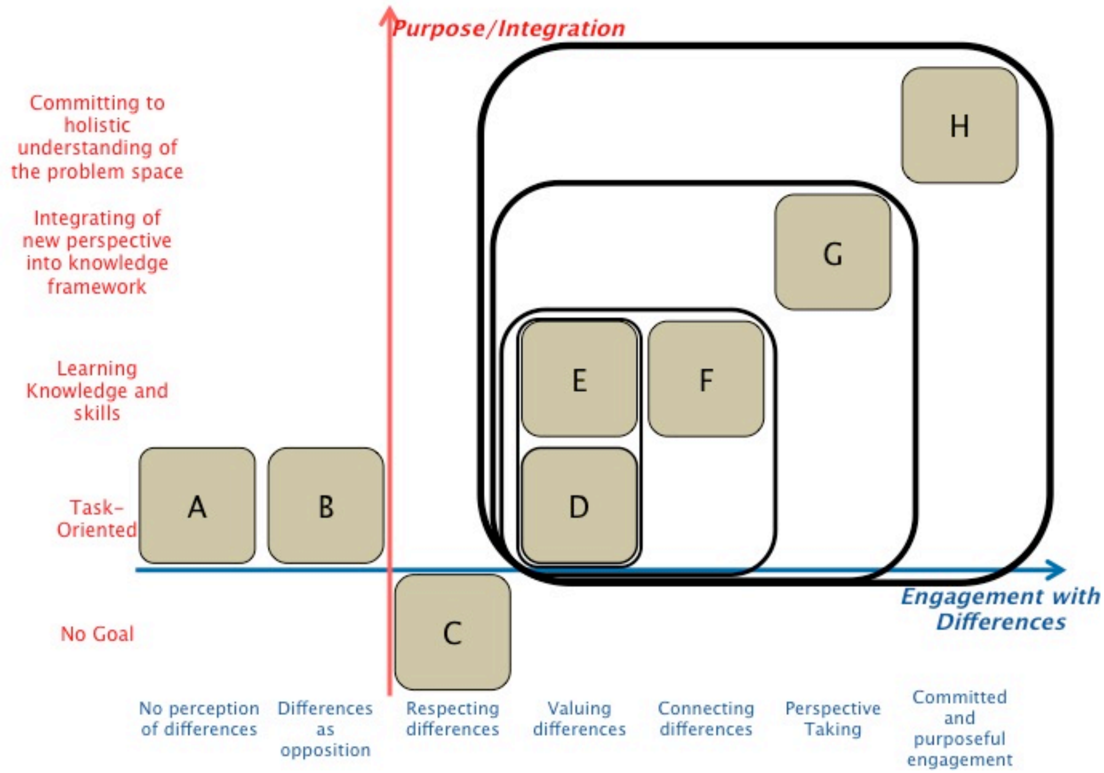

Figure 4.2 Outcome Space of Students' Ways of Experiencing Interdisciplinary Learning with Hierarchical Relationship

4.4.1 Category A Differences

The first category describes *IDPLE as no awareness of differences*. Interdisciplinary learning is experienced as learning of general skills of communication and project management without engaging the differences the others bring. The students whose experiences formed the other categories had also found these skills to be important but for the purpose of communicating ideas across a diverse others, which is illustrated by the following quote from Brett's experience in Category E, *IDPLE as bridging differences*. Brett participated in a service learning project where they broke down into sub-teams to work on the software and the hardware components separately. Being able to communicate in an effective manner between the different groups was a challenging aspect.

In between team meetings, when I was by myself working on the solution, I didn't know exactly what the other disciplines had in mind, or exactly what they wanted me to do, you know, exactly how I should engineer my solution to be compatible with theirs, you know. And it's not that we don't talk during our team meetings, or they don't tell me what they need to tell me; it's just things like that come up all the time, you know, and you have to have constant, I guess, cross-talk between two disciplines, or two different parts of the solution, you know. So I guess just knowing what's inside your partner's head, I guess, would be the thing.

Not including differences that others bring when engaging in interdisciplinary learning represented the critical different between Category A and the rest of the categories. Therefore, Category A constitutes a unique category that is self-inclusive.

4.4.2 Category B Differences

Student's experience in Category B *IDPLE as control and assertion* recognized that the differences others bring played a huge part in the interdisciplinary experiences. However, instead of understanding why multiple perspectives should be engaged, the differences were viewed as opposing to goals of one's own. The goal of learning was to know enough about what the other disciplines represented to know how to navigate and "control" the situation when the others' goal was not aligned with one's own. Within the outcome space, Category B represented a threshold concept (Meyer & Land, 2003, 2013; Zoltowski et al., 2012) in the axis of *engagement with others*. Although student experiences in this category presented a goal of learning, the antagonistic view of different others limited the students' engagement and understanding of interdisciplinary learning. This characteristic distinguishes Category B from the other categories.

By contrast, Eli, whose experiences were included in Category D, understood that the people with complementary skill sets were necessary to tackle tasks that are slightly more complicated. Instead of working against one another, interdisciplinary learning was about accommodating others' ideas and opinions and working towards the end goal.

And it's to see how people, like different engineers, the way they think and stuff, and how you can accommodate people's needs to, I guess, deliver the same goal, because everyone has different ideas from those engineers.

The opposing attitude and controlling behavior towards people from other disciplinary background is a critical difference between Category B and the rest of the categories. The experiences in Category B therefore form a distinctive category that is self-inclusive, similar to Category A.

4.4.3 Category C Differences

The third category, *IDPLE as coping with differences,* describes engagement with people by coping with different needs, priorities, or cultural norms. Rather than taking a stance against the differences like the prior category, the student in this category, John, was understanding of the circumstances of others when working with them. John made efforts to accommodate others' needs when it came to scheduling, and he also was not judging when coming across people whose time concept and communication style were different from his.

However, while differences were valued in a positive way, focus on the goal of learning experience was lost which was revealed by the lack of reflection how differences affect the intended goal of learning. For example, John mentioned the learning experience as an opportunity to learn, but when describing the concrete experiences he had, having to deal with the issue of coordination overwhelmed his experience. Therefore, Category C represented a threshold concept in the *goals and integration* axis. The lack of goals in the experiences had limited the student's understanding of interdisciplinary learning which was different from the other categories.

Inclusion of differences not only in disciplinary perspective but also in other background characteristics was not exclusive to this category. For example, Mark in Category E had a co-op experience which he considered to be interdisciplinary. He worked with people that were older and had different priorities.

Interdisciplinary doesn't just mean working with different majors and, I guess, different groups; it means learning to work with people just of completely different backgrounds, completely different age. I mean, different sex, too. I mean, interdisciplinary just doesn't relate to knowledge, it relates to just everything else that incorporates their life. So, I mean, he had a family; I wasn't worried about a family at the time. He was really into cars; I wasn't into cars at that time, but I did like cars, and now I love cars. So that's all he could talk about, and my thing was doing the EV Grand Prix, kind of. Yeah, it was just different likes and dislikes that you had to learn to kinda be familiar with just so that you could share a conversation or be able to cooperate with them.

Similarly, Alice in Category E also observed the differences in ways of seeing thing because of people's background beyond disciplinary differences.

I've grown a lot in being a mentor because the types of questions and the way that people think is different, no matter if you're from a different region or if you are from a different country or if you're just in a different discipline. The styles in which you speak and communicate as well as think are very different from people with a different background. And it's been interesting for me to be able to mentor people from different backgrounds because you can never . . . honestly and truly plan for the types of things they're going to ask or be concerned about.

Furthermore, the scheduling and coordinating issues were mentioned throughout the other categories, as illustrated by Anna in Category D.

It was also very different because everyone was very busy—I mean, not that people weren't busy on the other team, but everyone was very busy and it wasn't a very high priority, and so it kept being pushed off and off, and so it was hard to be able to actually get anywhere.

Even though students whose experiences comprised the other categories had similar experiences of having to include differences other than disciplinary, the distinction was that they were not overwhelmed by the differences and instead had a goal of interdisciplinary learning in mind, may it be working on a task, learning knowledge and skills, etc.

A lack of learning goals when engaging differences in interdisciplinary learning experiences represented a critical qualitative difference between Category C and the rest of the categories. Therefore, within the outcome space, Category C represented a self-inclusive category.

4.4.4 From Category D to E

The fourth category, *IDPLE as navigating creative differences*, described interdisciplinary learning experiences as task-oriented, in which students worked with others with complementary skill sets to achieve the goal of the task. They were in a partnership with others, letting others contribute where appropriate while putting their own strength forward. Others might present unique ideas regarding a specific task, and negotiating and understanding is required to achieve convergence in perspectives.

A critical variation between Category D and Category E, *IDPLE as learning from differences*, was viewing the experience as a learning opportunity while engaging with others and working though tasks. Others were not just people that brought in ideas but also served as resources for learning. Aspects of Category D were exhibited by experiences that formed Category E. In category E, Ash emphasized pooling different ideas from different people, which was one emphasis of Category D, but at the same time, she also stressed her experience of always learning something new from the others who possessed a different skill set.

I feel like it's very beneficial because there's so much you learn. Even though sometimes you learn really tiny things that other people in other disciplines come across and they work hard to figure something out, but now, you know, OK, it's like this, only because you've been in a team with some of those people. I'm still a sophomore, and freshman year and sophomore year, even later, it would help because you get so many different ideas, and putting them all together really helps come up with what your project needs. So, when there are people from different fields, it's like . . . they have different ideas than you have, so it helps.

Actively perceiving what was being learned while working with others was the key characteristic in understanding the critical differences between Category D and E. In addition to pooling ideas with others to achieve the goals of the tasks like experiences in Category D, students in Category E also viewed it as an opportunity to learn new knowledge and skills.

4.4.5 From Category E to F

A critical variation between category E, *IDPLE as learning from differences*, and Category F, *IDPLE as bridging differences*, was the focus on ways that could be used to enhance collaboration and information sharing in the learning experiences. While still engaged in problem solving and knowledge or skill learning, deliberate consideration was given to mitigate the differences in F, which was reflected in students' experiences of reflection and engagement of the collaborative and communicative matters. Ways to achieve that, as illustrated in the experiences of the students that constituted this category, were to focus on the intersecting connections between people working on different tasks. The characteristic of learning new skills to mitigate difference was illustrated by Mo's experience.

Of course I understood what the mechanical side was doing, but I had no idea what the computer engineers were doing. But to keep up with them, to understand what they were doing, I had to, myself, learn a bit of C computer language and try to understand what was going on so I know where they are at different points of time, and so I can tell them how to approach this problem and how to progress.

Brett also explained how learning common core could be helpful for the purpose of communication to other engineers.

Because every engineer is going to have to do a bit of software coding; to what extent is the question. Every engineer is going to have to analyze how their solution can fail, you know. So there are a lot of central ideas to engineering, despite your discipline.

The experiences of Category F represented a more comprehensive way of understanding interdisciplinary learning than those in Category E because of the deliberation in working and learning with others.

4.4.6 From Category F to G

A critical variations between students whose experiences lied in Category G, *IDPLE as expanding intellectual boundaries*, from those in Category F, *IDPLE as bridging differences*, was that they questioned the boundary of their own perspective, particularly in challenging their own view on what engineering work should entail. Rather than merely working, learning, or collaborating with different others, students in category G started to incorporate a more comprehensive perspective into their own knowledge system. For example, Mandy's interdisciplinary learning experience changed her perspective of what engineering work should be like. Learning to integrate perspectives other than engineering and technology has become an essential part of how she thought about working as an engineer.

Whereas working at the company, now I know how to have a good conversation with someone who is a sociology major. I think a lot of times engineers are like, "Oh we're so smart, we're so cool. No other majors are really important." But for me, those were really important parts of the work we did: how the technology came together with the other pieces. And so I came to value kind of like the soft sciences and the more, like, marketing and businessy side, too, not just the technology

In another example, Jasmin in Category G concluded that being able to see the impact of her design for a global client have effected how she sees design in general.

You know, in mechanical engineering, you take a sophomore design class, which teaches you, you know, look at your customer requirements, do your market research, understand who's going to be receiving this product, and yes, yes, yes, you do all that, you do all that research. But when you actually see the implications, it's such a huge, radical difference between what you generally think about when you're doing engineering design. If you're doing engineering design for like an American product, in this general area of the world, it's, you know, what you're used to. But having done this experience, and having to take a step back and completely reevaluate things, I think it teaches you to take a much broader approach to the initial phase of the design, regardless of the market that you're designing for

The two examples above were in contrast with the examples from Category F. Although Mo (F) emphasized communicating across disciplines, he had limited his interaction to other engineers only.

I mean, again, it gave me, as I said before, this perspective that for most of the projects you have to . . . different engineering fields do come together to get that project done, and *communication between those different fields is very important, and that's why engineers should have knowledge of all different fields, at least basic knowledge, so that they know what ____ (their? other? 32:37) team is doing and so that they can communicate better with them. Again, having had that experience, I feel myself lucky that I understand that now as an engineer.*

Attending only to technical issues was also apparent in Alice's (F) experience. She sought outside perspective on their team's design of a mathematics game board, but she limited the feedback to the "technicalities" of the project, in cost, material, and difficulty of the mathematics problems.

The more I'm in it, the more I see how valuable that actually is, because getting feedback from people who also have a completely external view of the situation is really important because they provide insight into technicalities that we, as students and designers, just didn't think of. And having them raise questions, and at least making us think about it, is sometimes enough to completely reinvent an element of a project. I think our bingo board underwent at least three iterations before we ever tested the first time. And then it got changed again between testing and delivery.

The experience in Category G is a more comprehensive way of experiencing interdisciplinary learning than those of Category F, as illustrated by the above examples. The critical variation between the categories included consideration beyond technical perspectives and integration of the more comprehensive perspectives into how the students thought about problem solving.

4.4.7 From Category G to H

A critical variation between Category H, *IDPLE as commitment to holistic perspectives*, and Category G, *IDPLE as expanding intellectual boundaries*, was the commitment to a more holistic understanding of the problem. Although students whose experience constituted Category G were beginning to perceive points of view beyond technical consideration, they still had doubts regarding how those new perspectives could be balanced with the technical consideration, as demonstrated by Bri.

So I guess, like, all the technical knowledge that . . . like I'm studying to be a chemical engineer, like those specific details that make me distinctly that type of engineer may not have come into play in my interdisciplinary work, but I think a lot of the broader context of, like, that I am an engineer, I guess the engineering mindset, more of the methods I've learned, come into play in those projects, versus like the specific techniques of my specific major coming into play thus far. I think that's kind of how I see it right now, yeah.

In comparison, students in Category H believed that viewing problems from interdisciplinary perspectives was the only way to gain a more comprehensive understanding, especially when dealing with complex problems, as illustrated by Saylor.

*Had somebody asked me before, I never would have had any negative views on it [*interdisciplinary learning*], I never would have ever said that I think that, you know, "Oh, well, you guys can go do your thing on your own, and we can do our thing on our own." But I think that I've definitely been opened up to how . . . Before, it seemed like, wow, that's a great idea to do. Now, it seems necessary, completely necessary, and it feels like things can't really even be accomplished well at all unless you have a very well-rounded team, at the very least a team that is very open to reaching out to other places and people to get information. So I think that yeah, it definitely has changed my perspective on it.*

Saylor further illustrated how consideration of a more comprehensive perspective should not be limited to a foreign context but with every problem.

So I think that the other nice thing about this whole setup is that when you're bringing two people together from such a different vantage point, and putting them together to work on a project, they're constantly learning from each other, they're constantly sort of *seeing things in a different way or finding . . . it could just be little things that they just find interesting all of a sudden, that they say, "Wow, that's something I've never thought about that an engineer thinks about, or something that I've never thought about that an anthropologist thinks about." So I think that that recognition that one type of specialty can't really complete any project to the greatest extent, to its greatest potential, I guess, is that first step in recognizing, OK, I can go ask questions. And I think it's a nice exercise . . . You know, because it's acceptable to go and ask somebody in a different field a question, and then it gets you comfortable with the idea of asking questions, and I think eventually kind of helps you ask even people in your own field questions, because you sort of realize, all right, in this very obvious setting, I can't do it myself, I have to ask you questions. And I feel like if you get more used to collaborating on that level, it makes it easier for you to go into any setting and be willing to ask even another engineer, even somebody else who has the exact same specialty as you, like, "Well, what is your opinion on it?" Because I think you start to see that even people from a similar background can have these varying, very varying (laugh) ideas, and the possibilities just kind of grow.*

Trey also showed his commitment to more comprehensive perspectives by evaluating the success of projects from other than engineering metrics.

You typically would have experience in engineering like you're presented a problem, you're given these statistics about it, or you're given these variables and these numbers to plug in, and you fulfill the problem and you get the answer, and that's usually the beginning of the end of it. Anthropology and other social sciences, I've realized now, bring a completely outside perspective where they're not dealing with these numbers but they're dealing with more of the qualitative and the end-user feedback in the information that they're getting. You know, their projects aren't considered successful based on whether or not your calculator was operating correctly that day. It's based primarily on, *you know, if the project is sustainable and it's community-driven and it's reliable and all these things.*

Their commitment was also exhibited by their purposeful engagement with others. They were proactive rather than reactive in their engagement. They not only purposefully looked for people with the right expertise but also anticipated the kinds of interaction that might take place between people. This was exemplified by Saylor's illustration of how she was bringing diverse people together.

And I think that this project is interdisciplinary in that it's bringing together two sides of campus to ask a lot of questions that either side wouldn't be able to ask on their own. And I think that that's—you know, I mean, there are a lot of things, too, that you could try to say are interdisciplinary, when you just kind of like put two differing majors in a room or differing fields in a room. But I think that the really cool thing about this project is that it's actually forcing both sides to ask those questions of each other, to say, "Well yes, I understand that that's where you're coming from, but also understand where I'm coming from," and trying to kind of meet in the center to produce something that is practical from all standpoints, instead of just from one or the other (laugh).

Trey also exhibited purposeful engagement with the different expertise by first understanding what they were capable of and then how they could fit into the team.

If I were just to dedicate my entire school career working on one of these projects, I would really only have familiarity working with civil engineers, and certainly the world isn't just comprised of civil engineers. So just getting a respect and an understanding for what MEs do—you know, what is their purpose and what are their specialties—and when I encounter them later on in a developing country or in the workforce, what kind of things can they bring to the table that I can utilize or [what kind of things] that I can offer them. And that applies not only to MEs but to all the engineering majors. Beyond that, working with people from the humanities and social sciences—and again, this is a new process for *us, but even through some of my classes, like even anthropology, that course, you're really exposed to what people outside of engineering can bring to the table, which for me this semester, even though I thought I had a grasp of what they're doing over there in the liberal arts department, you really have no idea. They think of things completely differently, in ways that problems are never presented in an engineering sense.*

The experiences in Category H represented a more comprehensive way of understanding interdisciplinary learning, as exhibited by Saylor and Trey. The experiences also showed the critical variations between Category G and H which included commitment to a more holistic understanding of the problem and purposeful engagement with different others.

4.5 Description of Experiences Across Categories of Description

Participants of the study were recruited strategically to represent a wide range of interdisciplinary learning experience and demographic characteristics as described in section 3.3.1. This section summarizes the distribution of the kinds of learning experiences in each category of description in Table 4.3, with the characterization of interdisciplinary learning experience referring to:

- **Curricular Characteristics**
  - *Curricular- Project*, which included any credit earning experience with project work. Examples included experiences in service learning program, the university's global engineering design program, cornerstone and capstone design.
  - *Curricular- Others*, which included any credit earning experience without project work. Examples of participants' experience included (i) a course that discussed household items from the perspectives of physics, chemistry, biology, and engineering, (ii) courses in economy and animal management that a participant linked to ideas in engineering, and (iii) a course discussing anthropologic

perspectives and their implication for development projects involving engineering elements.

- *Extra-curricular* activities, such as competitions and club activities with imposed structures such as deadlines. Examples of participants' extra-curricular activities included entrepreneur competition, solar-decathlon competition, a programming club project to simulate disease propagation.
- *Research* experiences, which included experiences associated with as undergraduate research program organized by the College of Engineering.
- *Internship*, co-op, or other work experience.
- *Informal,* which encompassed less structured experiences such as the Women in Engineering program, residential life, study groups, social groups and undergraduate mentoring programs.

- **Degree of Integration**
  - *Informed* interdisciplinary experiences were those motivated by questions from a particular discipline but informed by other disciplines (Lattuca, 2003), such as cross-listed courses. An example from participants' experiences included a psychology course on designing questionnaires that used biology or economy related questions. Another example included a participant's experience in engineering invention informed by his course experiences in economy and animal management.
  - *Synthetic* interdisciplinary experiences that combine identifiable disciplines (Lattuca, 2003). An example was a project designing assistive technology utilizing electrical, mechanical, and user experience perspectives. Another example was a course that analyzed household items from the perspectives of chemistry, physics, biology, and engineering.

- *Transdisciplinary* experiences that no longer associate with single disciplines but instead focus on concepts or methods that can be applied across disciplines (Lattuca, 2003) which were marked with "X" in Table 4.3. Participant experience sincluded (i) a course experience focusing on the central concepts of sustainability and using the disciplines only as contexts for application, and (ii) a research experience on creating nanofluid solutions that can be used across disciplines of electrical engineering, chemical engineering, and biology. Notice that even though experiences in category F, *IDPLE as bridging differences*, focused on finding intersecting skills and components particularly within the bigger field of engineering, those experiences did not fit the definition of transdisciplinarity as the motivation was not finding overarching concepts that could be applied across disciplines.
- A different definition of *transdisciplinary* experiences were ones shaped by consideration of particular context that might be social, cultural, environmental, etc. (Lattuca & Knight, 2010), and these experiences were marked with symbols of "*" in Table 4.3 to distinguish them from the previous definition of *transdisciplinarity*. Examples of these experiences included designing for para-athletes, community centers, or water resource facility while emphasizing the incorporation of user perspectives, or working on product design while focusing on the environmental impacts.

- **Engagement with Others**
  - *No partners or clients*, which included experiences in courses in which students worked solely and not with peers. There were no formal structures such as teaming in these experiences, although interactions such as discussions could be included.

- *Projects with team members or local users*, which included experiences in which students worked with teammates and/or clients that they could meet physically on regular basis. Examples of these experiences included service learning projects that focused on serving the immediate community around the campus area.
- *Projects with geographically distributed team members or remote clients*, which included experiences in which students worked with teammates, stakeholders, or users located not in the immediate area. All participants with experiences in this category were working on global design projects serving users or stakeholders in a non-U.S. location.

Table 4.3 Participant Experience and Demographic Information.

					Characteristics of IDPLE											
					Curricular Characteristics						Degree of Integration			Engagement with Others		
Category	Experience of	Year	Major	Sex	Curricular- Course	Curricular- Project	Extra-Curricular	Research	Internship	Informal	Informed	Synthetic	Transdisciplinary	No team member	Team Member/	Distributed Team/
A	Nash	Freshmen	FYE	M		X						X			X	
B	Abe	Senior	ME	M	X	X					X	X			X	
C	John	Senior	ECE	M		X			X			X			X	
D	Anna	Junior	ABE	F		X						X	*		X	X
	Eli	Junior	ME	M		X						X			X	
E	Kelly	Sophomore	ABE	F	X	X				X		X		X	X	
	Jules	Senior	IDE	F		X				X		X			X	
	Ash	Junior	CE	F		X		X		X		X			X	
	Adrian	Senior	AAE	M		X		X				X	X	X	X	
	Henry	Senior	ECE	M	X	X					X	X		X	X	
	Mark	Senior	ECE	M		X	X		X			X			X	
F	Mo	Senior	ME	M		X		X		X		X		X	X	

Table 4.3 Continued

	Alice	Junior	MSE	F		X				X		X			X	
	Brett	Junior	BME	M		X	X					X			X	
G	Jasmin	Senior	ME	F		X						X	*		X	
	Bri	Junior	ChemE	F		X						X	*		X	
	Marna	Senior	MDE	F	X	X	X					X	*	X	X	
	Helen	Senior	ChemE	F	X	X		X				X	X*	X	X	
	Mick	Senior	ABE	M		X						X	*		X	X
	Mandy	Senior	BME	F		X			X	X		X	*		X	
H	Trey	Senior	CE	M		X						X	*		X	X
	Saylor	Junior	CEM	F		X			X			X	*		X	X

CHAPTER 5. DISCUSSION

The study explored undergraduate engineering students' conceptions of interdisciplinary learning, particularly, the qualitatively different ways that students experience interdisciplinary learning. The study employed a phenomenographic methodological framework and used purposeful maximum variation sampling to recruit participants with various interdisciplinary learning experiences. The results of the study were the outcome space which consists of (i) two themes of expanding awareness, "engagement with others" and "integration and purpose" and (ii) eight categories of description of student experience of interdisciplinary learning, with the latter five forming a hierarchical structure. The results of the study have theoretical implication on our understanding of interdisciplinary learning in engineering in similar types of settings as well as on creating environments to facilitate interdisciplinary learning. This chapter focuses on the discussion of the results, limitation and implication of the study.

5.1 Discussions

In this section, I discuss how the results of the study, including the categories of descriptions and themes of expanding awareness, compare and contrast with past studies. To begin with, I discuss the threshold concepts that need to overcome for students to be able to experience interdisciplinary learning in a more comprehensive manner. Then, I consider how students learn and work with others in their experiences. In addition, I discuss how a transformative learning experience contrasts with an instrumental leaning experience. Also, I describe the parallel between the results of the study to the constructs of developmental theories. Finally, I compare the results to the ABET outcomes.

5.1.1 Threshold Concepts and Pre-Threshold Categories

The concept of threshold knowledge, which refers to concepts which are necessary for students to progress (Meyer & Land, 2003; Zoltowski et al., 2012), helps to explain the fact the category A, B, and C are not included in the hierarchical structure in the outcome space. Students need to overcome two threshold concepts in order to experience interdisciplinary learning in a more comprehensive way. The first threshold to interdisciplinary learning revealed by the study was valuing the differences of others as a possible asset to the task. Nash, whose experiences comprised Category A, *IDPLE as no awareness of differences*, did not recognize differences others bring as part of his learning experiences. Similarly, Abe, whose experiences constituted Category B, *IDPLE as control and assertion*, regarded other disciplinary perspective as against the engineering objectives. Failing to recognize the contribution of others has also been noted in other studies as one of the barriers to interdisciplinary collaboration in engineering teams (Richter & Paretti, 2009). Failing to recognize the contribution of others has also been described as being in the "island of knowledge", not having begun the journey of interdisciplinary understanding (Fruchter & Emery, 1999). Viewing the perspectives of others as wrong has also been considered as the very initial stage of intercultural development (King & Baxter Magolda, 2004). To be able to work and learn with others, efforts must be spent to understand and appreciate the contribution of others, which has been found to be the case in interdisciplinary collaboration of engineering education research as well (Borrego & Newswander, 2008). Experiences in Category C, *IDPLE as coping with differences*, crossed this first threshold, which was evident in the fact that John recognized the differences as potentially valuable and made efforts were to accommodate those differences by coordinating his schedule with others with different kinds of need. John's experience with others different from himself in age and family status helped him understand multiple realities. In the intercultural maturity literature, that has been recognized as an indication of progression through the development stages into the intermediate level as there is a "willingness to interact with diverse others and refrain from judgment" (King & Baxter Magolda, 2004).

The second threshold to interdisciplinary learning in the two-dimensional outcome space was having a purpose when engaging in the learning experience. Even though student whose experiences constituted Category C, *IDPLE as coping with differences*, crossed the first threshold in the interpersonal dimension, there was no integration of those differences into the problem solving aspect of the learning experiences. Having a personal goal has been recognized by other researchers as a first stage and a team goal the second stage of cross-disciplinary team learning (Schaffer et al., 2008). Boix Mansilla (2010) argued that establishing a purpose to guide learning process was one of the pillars of meaningful interdisciplinary learning (Boix Mansilla, 2010). In contrast, students whose experiences formed Category D, *IDPLE as navigating creative differences*, recognized that a common goal existed despite the differences, and they acknowledged others' ideas and incorporated them into the project after they evaluated them.

5.1.2 Learning and Working with Others

For students who valued the assets of different others and also had a purpose for interacting with different others, learning happened in interdisciplinary learning situations though co-constructing new knowledge and understanding with others. Participants whose experiences comprised Category D, *IDPLE as navigating creative differences, and* categories beyond went through the process of trying to understand others' thoughts and opinions by grounding and negotiating as a way of building a common solution. Dillenbourg (1999) argued that similar processes were necessary for collaboration learning: differences allow spaces for misunderstanding, and when partners misunderstand, they are made to build justifications and explain themselves. Galison (1999) described this as a *trading zone* that was set up by willing members to enable negotiation. Bormann (1996; 1985) described this process as reaching consensus through symbolic convergence. For those whose experience comprised Category F *enhancing collaboration*, further attention was given to setting up this trading space. For example, Mo and Brett learned common tools and languages of the other *tribe* in order to understand. Brett and Alice also considered using models or prototypes to convey specifications with others. These models and prototypes acted as a platform to convey the overlapping connections. Similarly, students in Category H, *IDPLE as commitment to holistic perspectives*, also had experiences of being in the *trading zone*. However, with a frame of reference that stood between engineering and other disciplines, they had learned to be in a more active role of leading and bridging people with diverse areas of expertise.

The results of the study suggested that even though students who participated in this study divided up tasks in their interdisciplinary learning experiences, they exhibited behaviors of learning and collaboration and beyond the simple *divide-and-conquer* description that even they used to describe how they would work themselves. It is perhaps to the students benefit that we point that out to them, and make them realize their interdisciplinary learning experience is really more comprehensive than they would consider.

5.1.3 Interdisciplinary Learning as Perspective Transformation

Transitioning from experiences of Category B to Category C and to Category D represented overcoming the two threshold concepts to be able to experience interdisciplinary learning in a more comprehensive way. However, there was also a quality of having to overcome a threshold in the main hierarchical cluster, particularly, transitioning from engineering-centered experiences (Category D, E, and F) to ones that included other points of view (Category G). Also, transitioning from Category G to Category H represented becoming committed to understanding of the problems with more holistic perspectives.

Students whose experience constituted Category G started to recognize alternative perspectives other than the technical aspect of problem solving that they were familiar with. Experiences such as dissonance (Vygotsky, 1980), disorienting dilemma (Mezirow, 1990), conflict (Brown Leonard, 2007), uncertainty (Baxter Magolda, 2004a) or discomfort (King & Baxter Magolda, 2004) were often described as a pre-requisite for a person to transform his or her meaning structure (Mezirow, 1997), which was what this study found regarding transforming perspectives for engineering students in interdisciplinary learning experiences. Individuals came across these experiences when their new experience collided with the way of thinking they had been using to make judgments. In this study of interdisciplinary learning experiences of undergraduate engineers, these experiences of dissonance arose from encountering more complicated social-cultural contexts of the problems at hand, specifically, when students started to wonder if having technical expertise was sufficient to deal with the problem hand and what it meant to view the task from a different perspective. In other words, the experiences of encountering a new perspective and feeling the dissonance created opportunity for further learning and perspective taking. According to the Piagetian notion, confronting different points of view might lead to assimilation and accommodation of the schema.

However, at the same time, students in Category G were not fully committed to the new perspectives. They had doubts on how to integrate the new perspectives with the technical knowledge that they had been learning and were comfortable with. It can be interpreted that the students were deeply acculturated in the engineering disciplinary values. Even after immersion in a different program, the engineering values still prevail. In contrast, students whose experiences formed Category H became committed to engaging in different perspectives in order to solve the problem in a more holistic fashion. The difference was that the students in Category H believed that engaging different perspectives was absolutely important and necessary and allowed them to see the problem from a more holistic perspective. They successfully accommodated the new information and created a renewed mental framework and moved into a more comprehensive way of experiencing interdisciplinary learning. Similar phenomena was observed in student experiences of resolving conflicting perspectives in an integrative liberal arts program (Brown Leonard, 2007).

This study did not set out to explore how the students were able reconcile their doubts or uncertainty. Jasmin's experience (Category G) showed a glimpse of the transition from uncertainty to conviction after seeing the implication of her design first hand as she saw how the users utilized it. It convinced her that incorporating a perspective that helped her understand the context of the task would be important

This whole project has been a really good lesson in looking at the whole picture. You know, yes, you're designing something, but you have to look at what you're designing for. And they teach you that in engineering, that's nothing new, but you don't really take it seriously—at least I didn't really fully take it seriously, and understand the implications of it, until I got extensive experience on the BUV experience.

Another example of having a firmer stance on having a more holistic perspective might be realizing the limitation of methods and approaches of one's discipline. Setup of Mick's prior project made him realized the constraints of only looking at a water problem from only the engineering perspective (see section 4.3.7 for more details).

Critical experiences such as that of Jasmin's or Mick's should be further explored to see how students overcome their reliance on technical-only perspective and integrate alternative frames of reference when viewing a problem. In practice, guiding students through the historical or cultural landscape of the problem might be a good strategy to prompt students to deliberately reflect on the perspectives that they take. This strategy is echoed in Nikitina's (Nikitina, 2006) work as one way to compensate for how interdisciplinarity is often reflected in the problem solving contexts. In theory, discussions and debates on how experiences of disorientation and dissonance lead to successful transformative learning could perhaps provide a framework of investigating these critical learning experiences in engineering, including the social and tool dependent nature of learning (Taylor, 1997), the effect of epistemological position (Perry, 1997) and cognitive complexity and prior experience (Brown Leonard, 2007), contextual factors such as the complexity of the problem (Julie Thompson Klein, 2004) have on interdisciplinary learning.

In summary, students were able to experience interdisciplinary learning more comprehensively when they encountered dissonance in a learning situation that required them to consider perspectives other than technical knowledge. Furthermore, having a commitment to a more holistic way of looking at problems was how some students were able to integrate other perspectives into their knowledge framework. How students respond to different perspectives was further explored as one of the two themes of expanding awareness that cut across all categories and are described further in the next section.

5.1.4 Themes of Expanding Awareness

The categories of experiences varied along two themes of expanding awareness: "engagement with others" and "purpose and integration" that formed a two-dimensional outcome space. As students were able to engage others with different expertise and perspectives, they were able to consider a more comprehensive view of the task at hand and integrate those perspectives into their knowledge framework. We have to consider both dimensions simultaneously to understand the students' interdisciplinary learning experiences within the scope of the study.

The finding suggests that in order for engineering students to experience interdisciplinary learning in a more comprehensive way, development besides cognition is necessary. Attitudes towards others and problem solving seem to play a role in students' interdisciplinary experiences. An attitude is a complex construct with cognitive, affective, and behavioral dimensions (Erwin, 2001), and it encompasses other constructs such as value and beliefs (Stern, Kalof, Dietz, & Guagnano, 1995). Furthermore, it might have intricate reciprocal and dynamic relationships with cognition and behavior (Schrader & Brown, 2008; Schrader & Lawless, 2004). In this particular study, the attitudinal factor was displayed in all categories, especially in the "engagement with others" dimension, from becoming aware in Category B, to appreciating in Category C, and to valuing and responding to the differences in Category D and onward, and finally to making commitment to such engagement in Category H. Believing that it was important to engage differences was how engineering students in this study were able to experience interdisciplinary in a more comprehensive way. The attitudinal dimension was also displayed in Category H in the "purpose and integration" axis, as the students believed that holistic perspectives were necessary in tackling problems. While the cognitive aspect of interdisciplinary learning and collaboration was deliberately discussed, such as integration of knowledge (Nikitina, 2005; Schaffer et al., 2012, 2008), the affective dimension was less explicit. When it is mentioned, it is often only a condition to initiate learning. For instance, "building appreciation" was a step towards interdisciplinary understanding in Fruchter and Emery's model (Fruchter & Emery, 1999) which implied an attitudinal aspect of learning. In order for students to experience interdisciplinary learning in a more comprehensive way, an attitudinal change must accompany learning and knowing.

The findings also suggests that another way to grasp the more comprehensive ways of understanding interdisciplinary learning is through understanding the interaction between the epistemic, interpersonal, and intrapersonal dimensions of learning. Exploring development from the three intertwining perspectives has been an effort to integrate theoretical perspective of student development to promote self-authorship (Baxter Magolda, 2009). In the results of the study, the epistemic aspect of interdisciplinary was especially salient in the "purpose and integration" dimension, reflecting a more developmentally mature view of interdisciplinary learning with the progression of beginning with instrumental learning (Category D, E, and F) and then transformative learning (Category G and H) (Kegan, 2009). Development in this dimension was also evident in the evolving awareness and acceptance of uncertainty and multiple perspectives. Growing maturity in interpersonal development meant an increased capacity to interact effectively with diverse others (Baxter Magolda, 2009; King & Baxter Magolda, 2004), which was evident in the "engagement with others" dimension. The intrapersonal aspect, which referred to students' identity-construction from relying on external formula to believing that self was central to the construction (Baxter Magolda, 2004b, 2004c, 2009), was less explicit in the outcome space. However, the initial level of development was implied in the lack of understanding of others in Category B (control and assertion), and that difference was viewed as a threat to identity. The intermediate level of identity development was signified by the recognition of other cultures from Category D onward, which implied a changing sense of identity distinct from own social groups' expectation. According to the model, the epistemic, interpersonal, and intrapersonal dimensions are interdependent, which corresponds to the results of the study that the two themes of expanding awareness have to be considered simultaneously.

In conclusion, I observed a parallel between the results of this phenomenographic study and constructs of developmental theories. Nuances of student experiences of interdisciplinary learning can be captured from dimensions beyond epistemic development, namely, interpersonal development, intrapersonal development, and attitudinal factors. It also implies that interdisciplinary learning potentially could help students develop maturity in those dimensions.

5.1.5 Comparison to Learning Outcomes

Accreditation is one of the important driving factors for incorporating interdisciplinary learning experience in engineering curriculum, thus it is worthwhile to compare the results of the study to the learning outcomes specified by the accreditation criteria. The results of the study suggest that engineering students' experiences of interdisciplinary learning exhibit the following ABET criteria:

3d. An ability to function on multidisciplinary teams

3g. An ability to communicate effectively

3e. An ability to identify, formulate, and solve engineering problems

3h. The broad education necessary to understand the impact of engineering solutions in a global and societal context

A survey of engineering alumni conducted by Passow (2012) revealed that understanding impact was rated significantly less important in professional settings than the other ABET criteria. The author argued that the results could inform faculty decisions on curricular emphasis. What the author meant was not to spend less efforts on the criteria that were rated less important but to find ways to embed technical knowledge in the context of professional competencies. The results of this study suggests the same:

understanding the impact and context of engineering work has the potential to elevate skills in teamwork, communication, and problem-solving, as evident in students' experiences that comprised Category H. Its implication on practice is that interdisciplinary learning experience could be more comprehensive when considering the multidisciplinary teaming criterion with other competencies on understanding impact of work, problem solving, and communication.

5.2 Limitations

While this study yielded new insight into interdisciplinary learning experiences, there were some limitations to the study. One limitation is regarding the scope of the study. All but two participants of the study all attended the same Midwestern land-grant institution in undergraduate engineering programs. The university serves about 40,000 undergraduate students and thus offers a variety of learning experiences available to students. The learning experiences, especially curricular and extra-curricular, that they described were limited to those provided by the particular institution. The experience associated with the particular institutional context might not capture the breath of interdisciplinary learning activities across the board. Another limitation regarding the scope of the study is that common experiences within the institutional context were the centered on working across perspectives. Other than that, interdisciplinary learning can be explored from other perspectives, such as learning for self-expression or innovation.

Another limitation concerns the variation of the sample of the study on the grade level of the participants. The bias could be introduced when I recruited. General emails were sent out and students who self-identified as having experienced interdisciplinary learning would sign up. Using this method, only one freshmen (Nash in Category A) and one sophomore (Kelly in Category E) signed up for the study. Given that all engineering students went through a freshmen engineering program in the particular institution, maybe students who were freshmen or beginning sophomores had less formed disciplinary identity. Thus, they were less likely to identify themselves as having an interdisciplinary experience. For example, the only freshmen Nash was in an interdisciplinary learning situation but was not aware of the disciplinary differences in his experience. More freshmen and sophomore participants would be needed to explore my assumption.

Another limitation is the data used for the study. I did not triangulate interview data with other kinds of product showing evidences. Other forms of data collection in a phenomenographic study could include group interviews, observations, drawings, written responses, and historical documents (Marton & Booth, 1997, p. 132), even though Richardson (Richardson, 1999) argued that they are "simply different forms of discourse that have the same evidential status as oral accounts". In order to maximize the variation of experience, I recruited from many different programs, making observation of any kind difficult. Having conducted an observational study earlier, I learned that by looking at the interaction and at the students' final deliverable would only allow me to see overt behavior such as communication but hard to learn about their own experiences.

The recruitment process may have privileged the formal academic experiences. Students did discuss less formal experiences, such as forming study groups (Kelly, Jules), being a resident assistant (Mo), undergraduate teaching assistants (Mo), ambassador to international students (Alice). They discussed roles that these experiences played in supporting relationship-building with different others and how that helped them understand and appreciate different others. These experiences were used in the whole transcript analysis approach to understand other parts of the transcript as a whole.

Another limitation is associated with using phenomenography. Since I was looking for variations that cut across all of the categories, there were nuances of interdisciplinary learning that I did not get to include as part of the outcome space, although the methodology allowed me to see the hierarchical structures between the categories of experiences that construed the outcome space. Such omitted nuances includes how students saw interdisciplinary learning as a mockup of their future work settings (Category D, E, and F), how being able to consider holistic perspective might allow empowering experience for the users (Saylor in Category H), relationship building and new connectedness with others as discussed earlier in this section.

Although most of these students participated in engineering design learning experience, which they would characterize as interdisciplinary, I did not specifically look at their conceptions through the lens of design thinking concepts and frameworks.

Lastly, regarding the outcome space, as discussed in section 5.1, the outcome space is not entirely clear on how students resolved conflicts and move from Category H to Category G. Furthermore, it is not clear how students would experience interdisciplinary learning when encountering a new learning situation. Regardless, it is important to maintain learning from and appreciating others, as the attitude is fundamental to interdisciplinary learning as revealed by the results of the study.

5.3 Implication for Practice

5.3.1 Implication for Teaching and Learning

One implication for teaching and learning is that engineering students do not automatically benefit from a multidisciplinary team experience in which students from different fields of study to solve problems. If students do not value the differences the other disciplines bring like the student whose experience formed Category B, they might work with others by trying to voice over others in order to feel in control of the situation. Instead of learning from others, the students might merely be "dealing with" the inconvenience of having people with different opinions or ways of looking at the problem. Another situation is that students might get overwhelmed either by the differences, either in opinions or people's lived experiences, such as the experiences of interdisciplinary as coping with differences (Category C).

There are a couple of ways that we can help students experience interdisciplinary learning in a more comprehensive way and overcome the threshold concepts of developing appreciation for other expertise and of having goals and purpose of learning. First of all, students need to get the sense that interaction with others is not just a nuisance imposed by the structure of the learning experience, which implies that it is imperative that students work on real problems with enough complexity that require contribution and interaction from people with different expertise. Complexity could for example arise from the open-endedness of the problem, time constraint, or lack of information. From the interview, students also mentioned how working on a real problem with real impact made them care. If there were real problem with real stakeholder and real implementation plan not possible because of the limited duration of the engagement, connection still can be made to entities on campus or in the communities.

Even when an authentic complex problem is in place, other strategies might need to be in place to make sure the see the relevancy of having different others on board. One such strategy could be having co-advisors from different fields that are relevant to the learning experience to display the importance of non-engineering perspectives. Interacting with experts could mean establishing a community of interdisciplinary practice for students to learn from the interaction and methods. From student experiences in Category G and H, having people with different expertise that carries credibility on the task is important to make sure other disciplinary perspectives have equal footing to that of engineering. A second strategy is to allot time for students to research the historical, social, and cultural background of the problem. If non-technical aspects get worked into the problem definition, it would mean engagement with those other perspectives early on in the experience. A third strategy is to encourage informal interaction between students of different disciplines. Less formal experience in social settings, student-formed study groups, as well as university resident experience were mentioned in the interviews as ways to build relationship with different others. Learning communities that connect curricular and extra-curricular experience is a good example of such pedagogical design.

Negotiation can be considered as a topic in the class to help students develop strategies for building common ground and making decisions. Research and study on negotiation is often done is disciplines such as management, business and organizational psychology, but it could be relevant to engineering education given proper synthesis.

Another implication of the results of the study to teaching and learning is that the outcome space could be used as a tool or a framework to facilitate students' reflection on interdisciplinary learning experience. For instance, students could already be engaging differences in positive ways in their team experiences (Category D) but not realizing it could also be a learning experience for additional skills and knowledge. (Category E). Also, they could be learning new ways to enhance collaboration with others (Category F). Another example is realizing that others' also have the experience of feeling unsure about approaching problems from perspectives that are not strictly technical. Furthermore, students would describe how they work with others as *divide and conquer*, but further exploration with them revealed that it was more nuanced as described in the category description, such as validating others' ideas, letting others contribute, and deliberately finding ways to improve communication with others. The outcome space therefore could potentially to make visible the interdisciplinary learning strategies that students are already using for them. Instructors can facilitate the process by asking students to reflect on the preconceptions they have, what they are already doing right, what can be changed in order to have a more comprehensive experience.

5.3.2 Implication for Curriculum

In the curriculum, we should consider providing opportunities to connect curriculum components to facilitate learning of other perspectives. For Mick whose experience was in Category G (expansion of perspectives), connecting design curriculum to anthropology classes was very helpful for him, although he only knew to take the anthropology class after failure to address user needs in a previous project. We could perhaps be more proactive in the approach by pointing students to general education classes to that might have relevance to understanding contexts of problems and point out how they might be relevant to the development of interdisciplinary perspectives.

Repeated exposure to interdisciplinary learning experiences has the potential to allow interdisciplinary learning in a more comprehensive way, given that students have overcome the threshold concepts. Prior interdisciplinary experience was identified as one of the catalyst for leadership of interdisciplinary problem solving teams in Klein's synthesis as well (1990, p. 131). One thing I learned from my participants, most of whom were juniors and seniors, was that by the beginning of their junior year, they were fully acculturated into engineering. For some, this meant seeing technical problem solving as *the way* to see a problem. By sprinkling interdisciplinary learning opportunities throughout the curriculum, make the intention clear, and make the connection to other courses clear, we may be creating a different culture in which interdisciplinary thinking becomes the norm of engineering.

Consider extra-curricular and informal experiences that foster relationship of students with different others. Although this was not explicitly discussed in the results section, participants with co-curricular interdisciplinary learning experience all mentioned the less formal experience as important in demystifying engineering as more important or difficult, which in terms helped their perception of the validity of other disciplinary perspective. Also, consider other kinds of experiences such as undergraduate research, co-op, and internship experience offers invaluable opportunity for students to experience integration of knowledge frameworks and to experience points of view from people with different experience levels.

Consider learning experiences combining the ABET criterion (d) an ability to function on multidisciplinary teams with other criteria, such as (c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability, (h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context, and (j) a knowledge of contemporary issues. As ABET left room for interpretation of what multidisciplinary teaming means in criterion (d), more emphasis is usually put on teaming then being multidisciplinary or interdisciplinary. Students might be able to experience interdisciplinary learning like those students whose experiences formed Category D, E, or F under this paradigm. However, combining criteria (c), (h), and (j), the team experiences might be more effective in allowing students to experience interdisciplinary learning in a more comprehensive way.

5.4 Implication for Research

To address the limitation of the study associated with the scope, future study could explore student experiences with the following characteristics:

- Beyond the institution context with different matriculation models;
- Beyond the kinds of learning situations included in the study,
- Beyond undergraduate students to include more mature learners, and
- Beyond interdisciplinary learning in the problem solving contexts. For example, what are interdisciplinary experiences anchored at the interface of engineering and art?

To address the limitation of using only interview data, future study might explore interdisciplinary learning competency with the outcome space of the study along with instruments or protocols that allow investigation of the cognitive, interpersonal, and intrapersonal development of students.

A closer look at how students overcome doubts about incorporating perspectives other than engineering would be informative to the engineering practice regarding what constitutes a critical experience to allow transformation of perspectives. Such a study could potentially use a longitudinal design and use reflective journaling as data collection methods.

Future study can also look through the lenses of design process and design thinking frameworks to look at negotiation and learning between students from different disciplines.

Besides disciplinary differences, future study might explore similarities and differences among competencies that require engineering students to engage with others, for instance, global competencies that requires engagement with culturally different others (Downey et al., 2006) and human-centered design competencies that requires engagement with users (Zoltowski et al., 2012). Furthermore, connections should be made to previous studies on cross-disciplinary practice of professionals (Adams et al., 2010). A holistic framework, such as self-authorship (Baxter Magolda, 2009; King, Magolda, & Massé, 2011), has the potential as it captures development in multiple dimensions.

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APPENDIX

APPENDIX

Screening Survey

1. What is your academic class? How many semesters of college have you completed?

2. Which academic department or program are you enrolled in?

3. Please check the **<u>interdisciplinary learning experience</u>** you've had and provide some details. These experiences might include:
   (To check the box, right click on the box, click on "Properties", and set "Default Value" to "Checked")

   ☐ Courses

   Please write down the title of the course you took and the department(s) the course was offered.

   ☐ Design Projects (such as EPICS, Global Engineering, Solae Decathlon, etc.)

   Please write down the title of the project.

☐ Research Projects (such as SURF)

Please describe the research project that you are/were involved with

☐ Other interdisciplinary learning experience

Please describe the experience briefly.

4. What are some of the disciplines involved in your interdisciplinary learning experience?

The following **demographic** information will ensure that the study sample is representative of the general population.

Are you: ☐ Male ☐ Female ☐ I prefer to not answer

Please check all categories that accurately represent your race, origin or descent:

- [ ] White or European-American
- [ ] Black, African-American or Afro-American
- [ ] American Indian, Aleut, or Eskimo
- [ ] Asian or Pacific Islander
- [ ] Hispanic
- [ ] Other ________________
- [ ] I prefer to not answer

Please provide us with your contact information so I can contact you to schedule an interview.

First Name__________

Last Name__________

[School Name] Email ___________

VITA

VITA

Ming-Chien received her Bachelors of Science in Electronics Engineering in 2004 from NCTU, Taiwan and her Masters of Science in Electrical and Computer Engineering with specialization in microelectronics and nanotechnology in 2006 from Purdue University.