Engineering Designers' Engagement and Inclusion of Diverse Perspectives in Engineering Work

by

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Abstract

Engineering is a sociotechnical discipline. Sociotechnical aspects of engineering work manifest in the societal impacts of engineering, the interactions between engineers and other engineers and stakeholders, and the societal norms or biases that engineers embed in their work. Given the interconnected nature of modern engineering problems, it is crucially important that engineers recognize and attend to the sociotechnical aspects of their work. Thus, there is a need for tools and pedagogies that support engineers in engaging with sociotechnical aspects of engineering work.

Our goals for this dissertation were to: 1) deepen understandings of how engineering students and practitioners engage with sociotechnical aspects of engineering work and 2) identify aspects of engineering students' and practitioners' perspectives and approaches that are transferrable to other engineering contexts and may thus inform tools and pedagogies. Chapters 2 and 3 of this dissertation investigated how engineering students and practitioners conceptualized sociotechnical aspects of engineering work based on their experiences. We synthesized eight statements that captured different sociotechnical aspects of engineering and, during interviews, asked participants to select two statements that aligned well with their experiences and two statements that did not align well. We also asked participants to share stories related to their selected statements and analyzed these stories to identify participants' beliefs about engineering work resulting from their experiences. We found that engineering students and practitioners both highlighted their engineering collaborations, more so than other sociotechnical aspects of engineering work. However, engineering students and practitioners understood the importance of

collaboration differently. Engineering students, in particular, indicated that effective collaborations did not require engineers to build close interpersonal relationships.

Chapters 4-6 investigated how engineering students engaged stakeholders in co-curricular and capstone contexts. Chapter 4 explored the needs assessment experiences of a co-curricular design team. During interviews, participants described several recommended practices for needs assessments, e.g., consulting diverse stakeholders, that they learned through their training and field work. Participants also described several challenges, e.g., accessing certain stakeholders, that impacted their approaches. Chapters 5 and 6 explored how six mechanical engineering capstone design teams engaged stakeholders to inform their projects. In Chapter 5, we analyzed recordings of participants' meetings with stakeholders and identified 22 distinct information gathering behaviors that participants exhibited during their meetings. Half of these behaviors aligned with recommended practices, and half did not align. We built upon these findings in Chapter 6 by analyzing additional data, including interviews with participants. We uncovered two main trends: 1) participants prioritized domain experts as information sources and 2) participants preferred early and decisive information gathering meetings.

Based on our findings, we have several recommendations for engineering education, practice, and research. Instructors should highlight the diverse ways that engineering is a sociotechnical discipline, teach students a range of approaches for engaging stakeholders, support students in gathering and analyzing multiple types of stakeholder data, and structure students' stakeholder engagement opportunities to encourage effective engagement approaches. In addition, engineering practitioners and students can use our lists of recommended stakeholder engagement practices in Chapters 4-6 to guide their stakeholder engagement approaches. Lastly, we recommend that engineering design and education researchers attend to the diverse ways that engineering is a sociotechnical discipline in their studies of engineering students and practitioners to more fully understand how various sociotechnical aspects of engineering work are connected.

Chapter 1 Introduction, Research Gaps, and Conceptual Frameworks

1.1 Introduction

Engineering is a sociotechnical discipline. Prior work has defined the sociotechnical aspects of engineering work in several different ways[1]. For example, engineering work is sociotechnical because the work performed by engineers inherently impacts and is impacted by broader societal contexts (Bijker, 1995; Leydens & Lucena, 2018; National Academy of Engineering, 2004). The societal impacts of engineering work manifest in myriad forms, ranging from climate change (Intergovernmental Panel on Climate Change, 2021), the distribution of transportation resources (Cantilina et al., 2021), and the development of devices to preserve human health (Zenios et al., 2010), to name just a few examples. Literature has also described how engineers' approaches to their work reflect their personal and social identities, including racial (McGee, 2020) and gender identities (Faulkner, 2009) and ability status (Holmes, 2018). In other words, engineering is not an "objective" discipline as has been traditionally thought; instead, engineering work is influenced by and perpetuates broader societal norms and biases (Riley, 2017; Valkenburg, 2021).

[1] In general, literature is inconsistent in defining how engineering is a "sociotechnical" discipline. Most sources define engineering as "sociotechnical" because of how the discipline impacts society and reflects societal norms. However, a notable number of sources instead define engineering as "sociotechnical" because collaborative activities play a prominent role in engineering work and engineers must navigate their collaborative interactions effectively. These definitions are typically provided separately and exclusively, i.e., few sources deal with both definitions. My personal stance is that both definitions are valid and relevant, i.e., engineering is "sociotechnical" because "all of the above." My use of the word "sociotechnical" in this dissertation is thus inclusive of both the broader societal impacts of engineering work and the interpersonal interactions between engineers. After all, both definitions capture ways that engineers' approaches are impacted by and influence societal norms and biases.

Engineering is also sociotechnical because it is highly collaborative (Jesiek et al., 2019; Trevelyan, 2010). Prior work has described how engineers spend much of their working time communicating and collaborating with other engineers (Anderson et al., 2010; Passow & Passow, 2017; Trevelyan, 2007, 2010). These collaborative interactions are necessary because no single engineer possesses all the knowledge needed to design and build modern technologies (Trevelyan, 2010). The sociotechnical nature of engineering work is further reflected in the ways that engineers bring their social identities and biases into their interactions with other engineers. For example, literature has described many instances of women and people of color experiencing interpersonal discrimination and microaggressions within engineering spaces (Doerr et al., 2021; McGee, 2020; Mejia et al., 2020). These harms often go unnoticed or ignored by engineers with majority (i.e., White, masculine, able-bodied, etc.) identities due to disciplinary norms that position engineering work as "objective" and separate from personal and social identities (Cech, 2013; Riley, 2008).

Another core sociotechnical practice in engineering is stakeholder engagement. A "stakeholder" is any individual who may impact or is impacted by the outcomes of engineering work (Dieter & Schmidt, 2013; Ulrich & Eppinger, 2012). Engineers engage stakeholders for various reasons, including to develop deeper understandings of the societal contexts of their work and to evaluate the feasibility of the products or technologies that they are designing (Dieter & Schmidt, 2013; Luck, 2018; Rosenthal & Capper, 2006). Engineers' engagement with stakeholders may range from one-time interviews with individual stakeholders (e.g., as described in Agarwal & Tanniru, 1990; Kouprie & Sleeswijk Visser, 2009), to community partnerships that last months or even years (e.g., as described in Agid & Chin, 2019; Harrington et al., 2019; Lucena et al., 2010).

Due to the sociotechnical nature of engineering work, and due to the growing dangers of global, interconnected societal challenges such as climate change, it is increasingly important that engineers approach their work in ways that attend to broader societal contexts and social identities. However, developing sociotechnical skills in engineering can be challenging. Sociotechnical topics such as stakeholder engagement and systems thinking are not consistently included within undergraduate engineering curricula (Schneider et al., 2008; Sienko et al., 2018). In addition, effective sociotechnical work typically requires engineers to collaborate with individuals, such as stakeholders and community partners, who may possess very different knowledge backgrounds, occupations, and positionalities from engineers (Leydens & Lucena, 2018; Mazzurco & Daniel, 2020). Thus, engineers must develop and adopt specific approaches for communicating across disciplinary barriers, building shared meanings, and developing equitable relationships (Adams et al., 2018; Harrington et al., 2019; Mazzurco et al., 2018).

Additional barriers to engaging with sociotechnical aspects of engineering come from cultural norms within the engineering discipline. For instance, literature has described a cultural knowledge hierarchy in engineering that positions technical knowledge (e.g., related to math and science concepts) as separate from and more important than social or interpersonal knowledge (Cech, 2014; Faulkner, 2000; Niles, Roudbari, et al., 2020). This "technical/social dualism" obscures the sociotechnical nature of engineering, and engineering students sometimes struggle to engage with sociotechnical aspects of engineering work as a result (Cech, 2014; Khosronejad et al., 2021; Niles, Contreras, et al., 2020).

Due to the challenges outlined above, and due to the importance of sociotechnical skills to modern engineering work, there is a substantial need for tools and pedagogies that support engineers in engaging with sociotechnical aspects of their work, including both contextual and interpersonal considerations. Thus, this dissertation explored how engineering students and practitioners engaged with sociotechnical aspects of engineering in curricular, co-curricular, and work settings. Our overarching goals for this dissertation were to: 1) deepen understandings of how engineering students and practitioners engage with sociotechnical aspects of engineering work and 2) identify aspects of engineering students' and practitioners' perspectives and approaches that are transferrable to other engineering contexts and may thus inform tools and pedagogies. Ultimately, through these goals, we hope to support engineers in successfully achieving the positive societal changes that they envision.

1.2 Organization of the dissertation

The work contained in this dissertation comes from two distinct research projects. The first research project, "Exploration of Student and Practitioner Perceptions of Engineering Experiences and Environments," investigated how engineering students and practitioners conceptualized engineering work and environments based on their previous experiences. The second research project investigated how engineering students in curricular and co-curricular educational settings engaged with stakeholders to inform their design work. This second research project included two separate studies: "Case Study of a Co-Curricular Engineering Design Team's Needs Assessment Practices" and "Comparative Investigation of Engineering Capstone Design Team Approaches to Conducting Information Gathering Meetings." We collectively refer to these two studies as "Exploration of Engineering Students' Stakeholder Engagement Approaches in Curricular and Co-curricular Design Contexts." These two research projects are connected in that both projects related to different ways that engineering is a sociotechnical discipline. Additionally, both research projects were primarily qualitative with a focus on understanding participants' perspectives and experiences in depth, i.e., they represent similar kinds of work despite substantial methodological differences. Both research projects also had a strong focus on the perspectives and experiences of engineering students, although the perspectives of engineering practitioners are also discussed in Chapter 2.

However, given the distinct perspectives on sociotechnical aspects of engineering work between the two projects, we often discuss these two projects separately through this dissertation. For example, within this introductory section, we first discuss the relevant research gaps, conceptual frameworks, chapter summaries, and additional published works related to our project "Exploration of Student and Practitioner Perceptions of Engineering Experiences and Environments." We then, separately, discuss the relevant research gaps, conceptual frameworks, chapter summaries, and additional published works related to our project "Exploration of Engineering Students' Stakeholder Engagement Approaches in Curricular and Co-curricular Design Contexts." This structure is followed throughout this dissertation and in our discussion section. We position our project "Exploration of Student and Practitioner Perceptions of Engineering Experiences and Environments" first in this dissertation for two main reasons. This project represents more recent research activities. In addition, this project had the broader scope, i.e., our goal was to investigate engineers' conceptions of engineering work overall, rather than a specific aspect of this work. The second half of this dissertation then explores a specific aspect of engineering work, stakeholder engagement, in depth.

1.3 Positionality statement[2]

I (the author of this dissertation) identify as a white man from a background of substantial educational and financial privilege. I was educated as a mechanical engineer through my

[2] The contents of this positionality statement were inspired by the orienting reflection questions found in Secules et al. (2021).

undergraduate education, although I also pursued other academic interests such as Chinese language and history. In addition to my research work, I am also a design instructor and have several years of experience teaching engineering design topics – including problem definition, stakeholder engagement, and the assessment of broader societal impacts – at the first-year, fourth-year, and graduate level. As a teacher, researcher, and mentor, I am deeply committed to fostering inclusive pedagogical environments and challenging inequitable structures in engineering.

Within this dissertation, my experiences as a student and instructor informed the research questions that we asked and the ways that we interpreted our data. For example, stakeholder engagement activities and instruction were largely absent from my undergraduate education. I saw this as a substantial educational gap that impeded my ability as an engineer to do socially impactful engineering work (and that almost led to my departure from the engineering discipline). My research on stakeholder engagement in this dissertation was thus motivated by my desire to 1) learn how to engage stakeholders effectively in engineering work and 2) learn how to teach this content effectively to other engineering students. Similarly, my research on how engineers conceptualize engineering work in this dissertation was in part motivated by my desire to better understand how engineers may be unintentionally and implicitly perpetuating inequitable cultural norms in engineering.

Closely related to my research questions, my positionality influenced my methodological choices. Simply put, I find qualitative data to be deeply interesting because of how this data reveals the details of individuals' experiences. To me, these details are crucial for identifying potential pedagogical implications of students' experiences and for revealing the more subtle impacts of engineering cultures[3]. Although I had not engaged in qualitative research prior to starting my PhD, I was already familiar with several of the goals and methods of qualitative research through my additional undergraduate major in East Asian Studies. However, qualitative research is not the norm in many engineering spaces. As a PhD student, I was able to do this dissertation work in large part because my departmental community uniquely recognized the value of qualitative engineering work and was able to support me in performing this work.

My background as a mechanical engineer-by-training influenced how I interacted with my study participants and how they viewed me. My engineering student participants often referred to educational experiences that they assumed that I shared, and in many cases they were correct. These commonalities in educational experiences helped me build rapport with my participants and ask appropriate follow-up questions to explore participants' responses. Similarly, my identity as an engineer-by-training also helped me build rapport with my practitioner participants and identify potential follow-up questions to explore practitioners' work experiences in depth.

Lastly, my social position as a PhD student at the University of Michigan influenced how I accessed my study participants. In the case of engineering practitioners, I was able to recruit several individuals through personal and institutional networks who were happy to help me with my dissertation research. In the case of engineering students, I had easy access to potential participants through instructor contacts and departmental panlists. It is unlikely that I would have been able to do this research without these institutional networks, and I am grateful to the various individuals who assisted me in recruiting participants.

[3] This is not at all to imply that quantitative research is not also valuable. Qualitative, quantitative, and mixed-methods research are all valuable for answering different types of research questions. The research questions that I am most interested in answering often align best with a qualitative research approach.

1.4 Exploration of student and practitioner perceptions of engineering experiences and environments

1.4.1 Research gaps

Prior work has highlighted various ways that engineering work is sociotechnical, ranging from collaborations between engineers to the impacts of engineering work on society (Leydens & Lucena, 2018; National Academy of Engineering, 2004; Trevelyan, 2010). All these sociotechnical aspects in some way intersect with engineers' daily work. However, **the extent to which practicing engineers attend to multiple and diverse sociotechnical aspects of engineering in their daily work is unclear**. In part, this research gap exists because prior studies of practicing engineers have mainly examined different sociotechnical aspects of engineering work separately. For example, Trevelyan (2010) conducted interviews with practicing engineers and workplace observations to reconstruct a description of engineering practice. Their findings highlighted how interpersonal interactions, between engineers with different expertise and between engineers and customers, were a core part of their participants' work. Anderson et al. (2010) interviewed engineers and conducted workplace observations at six different engineering firms to understand the work performed by engineers and engineers' identity development. Their findings similarly highlighted how communication and collaboration with other engineers was a core part of engineering work; their participants also seemed to view being a good team player as important to their engineering identities. Neither of these studies explored in depth the societal impacts of engineering work.

Other research has explored how engineers consider the societal implications of their work. For example, Mazzurco and Daniel (2020) compared how engineering students and engineering practitioners developed solutions for a simulated design problem related to the development of an alternative energy generation device for under-resourced settings. They found that, compared to students, engineering practitioners identified a range of considerations related to the technology, project stakeholders, and broader societal impacts. In addition, Pack et al. (2020) conducted interviews with 46 design professionals about how they considered and evaluated the societal impacts of their products. They found that almost all their participants were concerned about the societal impacts of their work, especially related to health and safety. However, Pack et al. (2020) also found that the use of specific practices to explicitly measure societal impacts was limited across participants. While these two studies highlighted how practitioners may engage with the societal impacts of engineering in their work, neither study explored in depth how engagement with societal impacts may intersect with other sociotechnical aspects of engineering work, such as collaborative activities with other engineers.

The extent to which engineering students recognize multiple and diverse sociotechnical aspects of engineering work is also unclear. Prior studies have described how engineering students may possess widely varying viewpoints on sociotechnical activities such as collaborating with teammates and engaging stakeholders in engineering work. For instance, in Meyers et al. (2012), engineering students were surveyed about the qualities that they felt were necessary to be considered an engineer. Participants consistently identified collaboration and communication skills as crucially important to being an engineer. By comparison, Dunsmore et al. (2011), in their investigation of student conceptions of engineering within an introductory manufacturing course, found that their engineering student participants frequently viewed their teamwork activities as an obstacle to overcome. Related to stakeholder engagement, Zoltowski et al. (2012) have described how engineering students' perspectives on stakeholder engagement may range from "Technology-centered" (i.e., no stakeholder involvement in design projects) to

“Empathic design” (i.e., deep stakeholder involvement and relationship building). Prior work has also described how engineering students may struggle to engage with the broader societal contexts of engineering work due to conceptions that engineering is a purely technical discipline (Khosronejad et al., 2021; Niles, Contreras, et al., 2020). However, as with prior studies of engineering practitioners, literature has mainly examined students’ perspectives and approaches related to specific sociotechnical aspects of engineering work separately, rather than exploring the ways in which students think across multiple sociotechnical aspects.

These two research gaps are important to address because engineers’ conceptions of engineering work influence how they approach their work in practice. For example, literature suggests that some engineers prioritize more technical aspects of their engineering work, such as the design and analysis of components, and as a result may de-emphasize the role that interpersonal interactions play in their work (Faulkner, 2000) and/or ignore the ways that their work impacts society (Cech, 2013; Riley, 2008, 2017). By investigating engineering students and practitioners’ conceptions related to multiple sociotechnical aspects of engineering work, our goal was to better understand the extent to which engineers recognize the diverse ways that engineering is a sociotechnical discipline. We also hoped to better understand how engineers apply diverse sociotechnical knowledge and skills in their daily engineering work, and the extent to which engineers may be inadvertently perpetuating normative conceptions of engineering as a primarily technical discipline.

The two research gaps outlined above represent the primary research gaps addressed by the set of studies included in this project (Chapters 2 and 3). However, there are two additional research gaps that are also partially addressed by this project. First, **it is unclear how engineering students and practitioners develop conceptions related to sociotechnical**

aspects of engineering work. While prior studies have described various ways that engineering students and practitioners may conceptualize or approach sociotechnical aspects of engineering work, few studies have explicitly explored how engineers develop their conceptions. Generally, literature (e.g., Carberry & Baker, 2018; Lutz & Paretti, 2021) suggests that engineers develop their conceptions of engineering work through their educational and professional experiences. However, more work is needed to identify specific aspects of engineers' educational and professional experiences that may be most influencing how engineers conceptualize sociotechnical aspects of their work. Thus, in addition to exploring how engineering students and practitioners may conceptualize engineering work, this dissertation also explicitly explored participants' conceptions within the context of their prior experiences.

In addition, **the extent to which engineering students' conceptions of engineering work align with engineering practitioners' conceptions is unclear.** A unique aspect of this dissertation work was that we gathered data from both engineering students and engineering practitioners using the same research methodology. This enables us to draw connections between students' and practitioners' responses to 1) identify specific similarities and differences in how students and practitioners may conceptualize engineering work and 2) identify potential reasons for these similarities and differences. This comparison may further deepen understandings of how engineers acquire their conceptions of engineering work and may also highlight the specific role that education and work environments play in informing engineers' conceptions. Collectively, our findings from this part of the dissertation may ultimately be used to inform pedagogies that support engineers in developing more comprehensive understandings of engineering as a sociotechnical discipline.

1.4.2 Conceptual framework: Enculturation and core ideologies within engineering cultures

This research was informed by literature describing dominant cultural ideologies in engineering and the ways that engineering students may acquire these ideologies. "Enculturation" is the process by which individuals learn and assimilate the knowledge, practices, and values of a culture (Carberry & Baker, 2018; Richard et al., 2016). Literature has described several ideologies that characterize engineering educational and work cultures and likely influence engineering students' professional identity development. Three ideologies in particular – *the technical/social dualism*, *depoliticization*, and *meritocracy* – have been often highlighted in literature because of how they contribute to a "culture of disengagement" in engineering that positions social justice concerns as separate from and irrelevant to engineering work (Cech, 2013, 2014; Niles, Roudbari, et al., 2020). This project sought to understand how students' and practitioners' perspectives related to all three ideologies, although the work ultimately included in this dissertation mainly relates to the *technical-social dualism*. These three ideologies are closely related; thus, all three are described below.

The *technical/social dualism* is an ideology within engineering that positions technical knowledge as separate from, and more important than, "social" knowledge (Cech, 2014; Faulkner, 2000; Niles, Roudbari, et al., 2020). In Faulkner's (2000) original formulation of the technical/social dualism, "social" knowledge referred mainly to skills for collaborating effectively with other engineers and/or incorporating user considerations into technologies. More recent descriptions of this dualism have expanded definitions of "social" to also include the range of competencies needed to engage stakeholders and understand the broader societal implications of engineering work (Cech, 2014; Niles, Contreras, et al., 2020; Niles, Roudbari, et al., 2020). Engineers whose understandings of engineering conform to the technical/social dualism may thus struggle to recognize intersections between the technical and collaborative or societal aspects of their work. This ideology can also lead engineers to ignore or devalue the contributions of individuals that they perceive as acting in more “social” ways. The contributions of women engineers are often marginalized in this way due to gender stereotypes that depict women as more “social” regardless of their actual technical competence (Faulkner, 2000; Riley, 2017; Tonso, 2006).

The ideology of *depoliticization* positions engineers’ personal, social, and cultural values as separate from their work and their interactions with other engineers (Cech, 2013, 2014; Niles, Roudbari, et al., 2020). This ideology suggests that engineering work is and should be “objective,” i.e., it is experienced the same way by everyone and is uninfluenced by individual biases. This ideology obscures the fact that disciplinary norms in engineering are heavily influenced by cultural norms of Whiteness and masculinity, since historically White men have held the most power in engineering spaces (Cech, 2013; Riley, 2017; Secules, 2017). When individuals, and especially women and people of color, attempt to practice engineering in ways that violate these norms (e.g., by emphasizing the community-focused aspects of their work or making an explicit commitment to public welfare), they are accused of polluting the objectivity of engineering with their own biases (Cech, 2013; Riley, 2017). The ideology of depoliticization thus obstructs critical engagement with other inequitable norms (such as the technical/social dualism) that characterize engineering spaces.

The ideology of *meritocracy* has been cited as a third cultural component that intersects with the technical/social dualism and the ideology of depoliticization to perpetuate inequities in engineering spaces (Cech, 2013, 2014; Niles, Roudbari, et al., 2020). According to this ideology, personal and career successes are primarily the result of individual talent, training, and hard work (i.e., “merit) (Slaton, 2015; Cech, 2013; Carter et al., 2019). This ideology, by encouraging a focus on individual capabilities, obscures how structural inequities impact access to opportunities. Thus, engineers who believe in the ideology of meritocracy may interpret broad societal inequalities to be the result of fair processes, rather than the result of deliberately designed inequities (Carter et al., 2019; Cech, 2013; Doerr et al., 2021). This mindset may lead engineers to conclude that addressing societal inequalities is beyond the scope of their responsibilities as engineers, and can also encourage deficit-based thinking and discriminatory behaviors (McGee, 2020; Mejia et al., 2020; Seron et al., 2018).

Engineering students and early career engineers are exposed to each of these ideologies through their education and professional training (Cech, 2014; Niles, Roudbari, et al., 2020; Seron et al., 2018). These ideologies, in turn, impact how engineers approach sociotechnical aspects of their work. For example, prior studies have shown that engineering students may struggle to reconcile stakeholder engagement work with their conceptions of engineering as a purely "technical" discipline (Niles, Contreras, et al., 2020), and may also consider public outreach to be outside the scope of engineering work (Khosronejad et al., 2021). These observed challenges may be explained, in part, by ideologies of depoliticization and the technical/social dualism in engineering. Thus, in this dissertation, we interpret our participants' conceptions of sociotechnical aspects of engineering work through the lens of cultural ideologies in engineering. We seek to understand the extent to which our participants' approaches align with and may be explained by these ideologies in engineering, and also identify ways that our participants may be inadvertently perpetuating these ideologies through their beliefs and actions.

1.4.3 Chapter summaries

In Chapter 2, we present a conceptualization of engineering as a sociotechnical discipline. This conceptualization is comprised of eight statements that focus on different sociotechnical aspects of engineering. We also describe a study that used these eight statements to explore the perspectives and experiences of engineering *practitioners* related to sociotechnical aspects of engineering work. This chapter represents work that is still in development and has not yet been published.

In Chapter 3, we describe a similar study as Chapter 2, but this time involving engineering *students* as participants. Together, Chapters 2 and 3 reveal key similarities and differences between how engineering students and practitioners understand sociotechnical aspects of engineering work, as well as the experiences that inform these respective understandings. The contents of this chapter were originally published as:

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A more complete version of this chapter, involving a more comprehensive analysis of students' conceptions of engineering work, is still in development. Table 1.1 shows how the contents of Chapters 2 and 3 compare to the research gaps identified in Section 1.4.1.

Table 1.1 Dissertation chapters 2 and 3 mapped to research gaps

Research gap	Chapter
It is unclear to what extent **engineering practitioners** attend to multiple and diverse sociotechnical aspects in their daily engineering work	2
It is unclear to what extent **engineering students** recognize multiple and diverse sociotechnical aspects of engineering work	3
It is unclear how **engineering students** and **practitioners** develop conceptions related to sociotechnical aspects of engineering work	2, 3
The extent to which **engineering students**' conceptions of engineering work align with **engineering practitioners**' conceptions is unclear	2, 3

1.4.4 Note about study contexts

The work described in Chapters 2 and 3 took place prior to and during the early stages of the COVID pandemic. Twenty-two out of 30 student interviews occurred in person prior to the pandemic. Eleven out of 28 practitioner interviews occurred prior to the pandemic – eight in person and three over the phone. All other interviews occurred after societal lockdown and were conducted remotely using a teleconferencing software such as Zoom. Given that we were still in the early stages of the pandemic at the time, the COVID pandemic did not feature heavily as a topic of conversation within participant interviews.

1.5 Exploration of engineering students' stakeholder engagement approaches in curricular and co-curricular design contexts

1.5.1 Research gaps

Stakeholder engagement is a core sociotechnical activity. Prior studies have described several benefits that engineering students may experience as part of engaging with stakeholders in engineering educational settings. In the context of specific design projects and activities, studies suggest that interactions with stakeholders can support students in developing engineering solutions that more appropriately address stakeholder needs (Hess & Fila, 2016; van Rijn et al., 2011). Interactions with stakeholders may also support engineering students in synthesizing product requirements that more accurately reflect stakeholder perspectives (Mohedas et al., 2015). More generally, participation in educational learning opportunities with substantial stakeholder involvement has been shown to support student growth in various areas, including cross-disciplinary communication skills (Gordon et al., 2018; Jeffers et al., 2015; Sienko et al., 2018), real-world problem-solving skills (Gordon et al., 2018; Jeffers et al., 2015; Sienko et al., 2018), and social responsibility attitudes (Rulifson & Bielefeldt, 2019).

Prior studies have also described several challenges that engineering students may encounter while interacting with stakeholders. For example, Bano et al. (2019) observed 110 first-year master of Information Technology students as they conducted requirements elicitation interviews for a simulated design task. They identified several challenges that their participants encountered while conducting their interviews, such as asking poorly worded questions, asking questions in an illogical order that interrupted interview flow, using language that might be confusing for the interviewee, and treating the interview more as an interrogation than a conversation. In addition, Mohedas et al. (2014) explored the experiences of three teams in a mechanical engineering capstone design course related to applying design ethnography methods. They found that their participants appreciated how design ethnography methods enabled them to gather design-relevant information from stakeholders. However, their participants also struggled to navigate inconsistencies and ambiguities in the information provided by stakeholders. In part, these challenges may emerge because instruction related to effective stakeholder engagement practices is not typically covered within undergraduate engineering curricula (Schneider et al., 2008; Sienko et al., 2018).

While these challenges have been described in prior work, **the exact ways that engineering students may be engaging with stakeholders in practice, particularly in curricular settings such as engineering capstone courses, are unclear**. This research gap exists because few prior studies have directly analyzed students' interactions with stakeholders (e.g., via transcripts of meeting recordings) within capstone courses. Relatedly, few prior studies have investigated the relationship between how engineering students interact with stakeholders during individual meetings and engineering students' overall stakeholder engagement approaches (including the individuals with whom students meet and when such meetings occur during design projects).

The result of this research gap is that it is unclear whether students' interactions with stakeholders are beneficial for students' design projects and skill development *because* students are leveraging effective engagement practices, or despite students leveraging ineffective practices. If the former, **prior literature has also provided few examples of effective practices that engineering students may be employing to engage stakeholders**. This information is needed to support engineering students in employing effective practices for engaging stakeholders and using stakeholder data to inform design projects. Thus, a goal of this dissertation was to deepen understandings of how engineering students in capstone settings may be engaging stakeholders, including practices that engineering students may be implementing effectively as well as challenges that have not been described in depth in prior work.

A separate, but related, research gap also exists related to needs assessments in co-curricular, community-engaged engineering environments. Needs assessments represent a specific type of stakeholder engagement activity that is conducted at the very beginning of community-engaged design projects. Designers conduct needs assessments to build relationships with their partner communities, understand community contexts, and identify possible foci for design projects (Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995). Engineering students are increasingly participating in community-engaged, co-curricular design projects, and many of these efforts have been described in prior literature (e.g., de Chastonay et al., 2012; Harshfield et al., 2009; McDaniel et al., 2011). Given the project context, these student projects likely involved some sort of initial problem definition or needs finding component that resembled a needs assessment.

Despite these prior literature examples of student-led, community-engaged design projects, **the extent to which engineering students may be applying recommended practices for community-engaged needs assessments is unclear.** Most literature descriptions of student-led community-engaged projects (e.g., de Chastonay et al., 2012; Harshfield et al., 2009; McDaniel et al., 2011) have focused on the development of the eventual solution, rather than the practices that students used to identify and evaluate community needs. This research gap is important to address because one key cause of community-engaged project failures is designers' poor understanding of stakeholder needs (Lucena et al., 2010; Nieusma & Riley, 2010; Wood & Mattson, 2016); without information on how students engage stakeholders in co-curricular project settings, it is difficult to determine whether students are investigating stakeholder needs effectively.

Relatedly, **it is unclear how contextual aspects of engineering students' co-curricular projects may impact their needs assessment approaches.** Many community-engaged engineering projects (e.g., as described in Aslam et al., 2014; Bryden & Johnson, 2011; Nieusma & Riley, 2010) occur in remote, rural communities with limited transportation and communications infrastructure. These settings present unique challenges that engineering students likely must navigate in their needs assessment activities. However, given the limited prior discussion of students' needs assessment activities in literature, few studies have described specific challenges that students may encounter in their needs assessment activities that relate to their project contexts. Thus, another goal of this dissertation was to identify contextual challenges that may impact students' needs assessment approaches, to inform pedagogies related to navigating contextual challenges effectively.

1.5.2 Conceptual framework: Characteristic differences between beginner and advanced engineering designers

Within the field of engineering design, a collection of literature has described a continuum of characteristic behaviors that differentiate beginner engineering designers from more advanced engineering designers (Atman et al., 2007; Crismond & Adams, 2012; Mohedas et al., 2016). "Advanced" designers are defined as individuals who approach their design tasks with greater levels of skill, often (but not always) because they possess greater levels of experience. We applied this idea, that there are characteristic differences between how beginner and advanced designers approach design tasks, as a framework that informed the work described in Chapters 4-6.

Engineering design projects are typically defined by two main characteristics: 1) the problem to be addressed is "ill-defined," i.e., engineers initially lack the information they need to identify and develop effective solutions, and 2) these projects are "open-ended," i.e., there exist a wide range of possible solutions, meaning that engineers must evaluate and compare various solution options to determine which options are optimal (Buchanan, 1992; Dieter & Schmidt, 2013; Goel & Pirolli, 1992). Literature suggests that beginner engineering designers and advanced engineering designers respond to the open-ended and ill-defined nature of design projects in characteristically different ways. For example, beginner designers are more likely to begin problem-solving without first developing a comprehensive understanding of their design problems and are also more likely to adopt a linear design process (Atman et al., 2007; Crismond & Adams, 2012). Advanced designers, by comparison, are more likely to explore their problem contexts thoroughly before developing solutions and continue to iterate on their understanding of their design problem as they develop possible solutions (Atman et al., 2007; Crismond & Adams, 2012; Schön, 1983).

Prior work by Mohedas et al. (2016) has applied the idea of beginner and advanced designer characteristics to design ethnography, i.e., the use of interviews, observations, and other data collection methods to gain a deeper understanding of stakeholders and design problem contexts. Within their model, beginner design ethnographers may adopt a "one-size-fits-all" approach to design ethnography, i.e., they may apply recommended practices (such as asking open-ended questions) but struggle to adapt these practices to specific stakeholders or situations. Beginner design ethnographers may also struggle to navigate the inconsistencies and ambiguities that may emerge as they more deeply explore their problem contexts. More advanced design ethnographers, by comparison, rely on personal experience to adapt their design ethnography approaches to specific contexts. They may also develop greater discernment as to which details or features within a context are relevant to their design projects, and thus target their activities to explore these features in greater depth.

This project applies the idea of beginner and advanced designer characteristics to interpret the practices of engineering students as they engage stakeholders to inform their open-ended engineering design projects. Literature has described several recommendations for stakeholder engagement and needs assessments; we have synthesized these recommendations into specific practices that we compare with the practices described or exhibited by our participants. In this way, we identify aspects of stakeholder engagement and needs assessments that our participants seem to be implementing successfully (i.e., practices that seem more advanced), and other aspects where our participants could use more support.

In addition, in applying this conceptual framework, we generally avoid labelling our participants themselves as "beginners/novices" or "advanced/experts." We do this for several reasons. First, with regards to stakeholder engagement, it is not always clear who is a "beginner" or who is "advanced." An engineer might have years of experience with the more technical aspects of engineering work and yet no experience interacting with stakeholders. Second, identifying a participant as a "beginner" just because they are a student potentially obscures the assets or other types of knowledge that students may be bringing to their projects that enable them to engage stakeholders effectively. Third, the recommended practices that we describe in this dissertation are drawn from literature, and thus theoretically represent "advanced" practices. However, it is unclear how well these practices align with the approaches of more "advanced" designers in practice, and there may be other practices that "advanced" designers exhibit related to stakeholder engagement that are not described in literature. Fourth, engineering students and early career engineers may exhibit characteristics of both "beginner" and "advanced" designers. Attempting to categorize participants' approaches obscures the nuance within these approaches. Our focus on our participants' specific *practices*, rather than their experience levels or other personal characteristics, is one way that we navigate the concerns outlined above. Ultimately, we seek to provide deep descriptions of engineering students' practices that can lead to deeper understandings of how engineering students develop their knowledge of stakeholder engagement.

1.5.3 Chapter summaries

In Chapter 4, we describe a case study related to the needs assessment practices of an undergraduate co-curricular engineering design team initiating a community-based, cross-cultural design project. This case study demonstrates students' learning gains resulting from their needs assessment experience, as well as barriers that affected their approach. The contents of this chapter were originally published as:

Loweth, R. P., Daly, S. R., Liu, J., & Sienko, K. H. (2020). Assessing needs in a cross-cultural design project: Student perspectives and challenges. *International Journal of Engineering Education*, *36*(2), 712–731.

In Chapter 5, we analyze transcripts of information gathering meetings conducted by six mechanical engineering capstone design teams with stakeholders and domain experts to inform their design projects. We describe a collection of 22 distinct student information gathering behaviors that were observed within these meetings. We categorize these behaviors based on their function within the meetings and their relationship to recommended practices. The contents of this chapter were originally published as:

Loweth, R. P., Daly, S. R., Hortop, A., Strehl, E. A., & Sienko, K. H. (2020). An In-depth Investigation of Student Information Gathering Meetings with Stakeholders and Domain Experts. *International Journal of Technology and Design Education*, *32*(1), 533–554. https://doi.org/10.1007/s10798-020-09595-w

In Chapter 6, we continue the analysis presented in Chapter 5 while also incorporating broader contextual information related to each individual team's respective information gathering approaches. We describe trends observed across teams related to whom teams met with, when these meetings occurred during the capstone semester, and the information gathering behaviors that teams exhibited within their meetings. The contents of this chapter were originally published as:

Loweth, R. P., Daly, S. R., Hortop, A., Strehl, E. A., & Sienko, K. H. (2021). A comparative analysis of information gathering meetings conducted by novice design teams across multiple design project stages. *Journal of Mechanical Design*, *143*(9), 092301. https://doi.org/10.1115/1.4049970

Table 1.2 shows how the contents of Chapters 4-6 compare to the research gaps identified in Section 1.5.1.

Table 1.2 Dissertation chapters 4-6 mapped to research gaps

Research gap	Chapter
The exact ways that engineering students may be engaging with stakeholders in practice, particularly in curricular settings such as engineering **capstone** courses, are unclear	5, 6
Specific ways in which engineering students may be applying recommended practices to engage stakeholders in **capstone** settings are unclear	5, 6
The extent to which engineering students may be applying recommended practices for community-engaged **needs assessments** is unclear	4
It is unclear how contextual aspects of engineering students' co-curricular projects may impact their **needs assessment** approaches	4

1.5.4 Note about study contexts

Chapters 4-6 originated as various studies (all pre-COVID) that were meant to evaluate the impacts of Socially Engaged Design Academy (SEDA) learning modules (*Socially Engaged Design Academy*, n.d.) on engineering students' learning in curricular and co-curricular projects. These learning modules were hosted by UM's Center for Socially Engaged Design (C-SED), where I (the dissertation author) ultimately worked for several years as a graduate facilitator. Thus, my proximity as an instructor to the studies described in Chapters 4-6, as well as the broader contexts of these curricular and co-curricular environments, is worth commenting on in depth.

In Chapter 4, the SEDA learning blocks played a substantial role in our participants' needs assessment training. These learning blocks included online knowledge checks and in-person coaching sessions. I, along with one other staff member (Aliya Jawad), graded participants' knowledge checks and provided feedback to participants. All coaching sessions were led by Aliya, who provided further feedback to participants. Based on our findings from this study, I subsequently updated the learning blocks on "Planning a Needs Assessment" and "Writing Needs Statements" to better support student learning. My findings have also informed

C-SED workshop content on conducting needs assessments and synthesizing stakeholder data into needs statements.

In Chapters 5 and 6, some participants (specifically, select members of Teams B and F) also completed SEDA learning blocks related to interviewing stakeholders. Unlike Chapter 4, I did not grade participants' knowledge checks. I also was not involved with the capstone course in any capacity, although several of the participants in this study were classmates of mine in a different course related to front-end design practices. We did not gather sufficient data to evaluate the impacts of the learning blocks on student learning in this setting. However, we did gather substantial data on how our participants engaged with their stakeholders in practice, and this data was valuable for clarifying the goals of future stakeholder engagement pedagogy. The outcomes of these studies have been used in several ways. Subsequent semesters of the capstone course have featured updated content on stakeholder engagement, and in many cases I delivered this new content myself as a guest lecture. The outcomes of these studies have also informed iterations to SEDA learning blocks related to conducting interviews with stakeholders and have informed C-SED workshop content related to interviewing stakeholders. Lastly, I developed a reflection tool for stakeholder interviews based on my findings from Chapter 5 and implemented this tool as part of a larger project within an introductory engineering class.

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Chapter 2 Sociotechnical Aspects of Engineering Work: Perspectives from Engineering Practitioners

2.1 Introduction

Engineering is a sociotechnical discipline, i.e., the processes and outcomes of engineering work are inseparable from societal contexts and considerations (Bijker, 1995). Engineering work impacts broader social (Kroes et al., 2006), cultural (Trevelyan, 2013), political (Valkenburg, 2021), and environmental (B. R. Cohen, 2021) systems; these systems, in turn, influence how engineers perform their work. Sociotechnical aspects of engineering work also include how engineers relate to one another, for instance when sharing information and navigating relationships (Jesiek et al., 2019; Trevelyan, 2010). These interpersonal interactions are strongly affected by engineers' personal and social identities (Fila et al., 2014; McGee, 2020).

Prior studies have, separately, investigated how engineers collaborate and communicate with other engineers (Anderson et al., 2010; Trevelyan, 2010), integrate diverse bodies of knowledge (Jesiek et al., 2021), and consider the broader societal contexts of engineering work (Mazzurco & Daniel, 2020). However, few studies have compared engineers' perspectives and experiences across different sociotechnical dimensions of engineering. Thus, our understanding of how engineers perceive and make connections between contextual-sociotechnical and interpersonal-sociotechnical dimensions of their work is limited. In addition, some sociotechnical aspects of engineering work have been relatively underexplored. For example, Mazzurco et al. (2021), in a review of literature on professional engineering practice, found that relatively few papers have investigated specific technical competencies of engineers. More information is needed to understand how engineers may conceptualize technical competencies within the broader sociotechnical contexts of their work.

Our study presents a novel, comprehensive framing of engineering as a sociotechnical discipline that includes both contextual and interpersonal dimensions and is grounded in the stated educational goals of engineering organizations and universities. We used this comprehensive framing to explore how engineers from a range of industries conceptualized and experienced various sociotechnical aspects of engineering work. Our findings describe several ways that engineers may understand sociotechnical aspects of engineering work, and highlight potential points of divergence between practicing engineers' perspectives and experiences and the aspirational visions of engineering espoused by engineering organizations and universities.

2.2 Background: Synthesis of engineering as a sociotechnical discipline

We reviewed descriptions of engineering work and core competencies found in reports from professional engineering organizations (e.g., National Academy of Engineering, 2004; National Society of Professional Engineers, 2013) reports from engineering universities (e.g., Graham, 2018; Kamp, 2016), and prior literature (e.g., Anderson et al., 2010; Trevelyan, 2010). Through our review, we identified eight themes that define various ways that engineering is a sociotechnical discipline[4].

Engineering is a technical discipline. The National Academy of Engineering (NAE), in their report on *The Engineer of 2020*, stated that "Engineering must be grounded in the fundamental principles of science and mathematics" (National Academy of Engineering, 2004, p.

[4] One limitation of our approach is that the sources we consulted did not directly discuss how engineers should account for their social identities in their engineering work. Social identities affect engineering work processes and outcomes, which is yet another way that engineering may be considered a sociotechnical discipline. See (Fila et al., 2014; Ozkan & Hira, 2021)

49) The Accreditation Board for Engineering and Technology (ABET) has similarly highlighted the ability to "identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics" (Accreditation Board for Engineering and Technology, 2022, sec. Student Outcomes (1)) as a core learning outcome for undergraduate engineering students.

Engineering is also constantly evolving in response to the changing needs of society. Modern engineers work in evolving fields such as software development, environmental sustainability, and industrial design (Magarian & Seering, 2021). The core engineering "body of knowledge" has correspondingly expanded to include, in addition to math and science, disciplines such as "computing, the life sciences, the social and behavioral sciences, business management concepts and skills, and entrepreneurship" (National Academy of Engineering, 2018, p. 6) The National Society of Professional Engineers (NSPE) has additionally emphasized "lifelong learning" as a core engineering capability that enables engineers to adapt to changes in engineering knowledge, technology, and tools (National Society of Professional Engineers, 2013).

Engineering involves synthesizing and integrating knowledge. Engineers bring together knowledge from multiple disciplines to solve complex problems (National Society of Professional Engineers, 2013). Kamp (2016), in their vision for higher engineering education, also emphasized that engineers must be able to synthesize information and perspectives from diverse individuals occupying various organizational or societal roles. These integrative aspects of engineering work have led researchers such as Jesiek et al. (2018) to refer to engineers as "boundary spanners."

Engineering is a creative discipline. Engineers employ divergent thinking to identify and explore diverse solution possibilities (Itabashi-Campbell & Gluesing, 2013; Kamp, 2016). The American Society for Engineering Education (ASEE), in a report on transforming undergraduate engineering education (American Society for Engineering Education, 2018), has also indicated that engineers should be able to deal with ambiguity, conflict, and plurality and employ critical thinking to make inferences or judgements. Other reports have additionally defined creativity in engineering as the ability to integrate and apply disparate knowledge in novel ways (Kamp, 2016; National Academy of Engineering, 2015). Thus, the integrative and creative aspects of engineering work are related.

Engineering is a team discipline. Studies of professional engineering practice have shown that engineers spend substantial time communicating and collaborating with other individuals as part of their engineering work (Anderson et al., 2010; Trevelyan, 2010). Passow and Passow (2017, p. 491), in their literature review of core engineering competencies, have further suggested that technical competence and collaboration skills are "inseparably intertwined." ABET and NSPE have similarly identified 1) the ability to "function effectively on teams" (Accreditation Board for Engineering and Technology, 2022, sec. Student Outcomes (5); National Society of Professional Engineers, 2013, p. 18) and 2) the ability to "communicate with technical and non-technical audiences" (Accreditation Board for Engineering and Technology, 2022, sec. Student Outcomes (3); National Society of Professional Engineers, 2013, p. 17) as core engineering competencies.

Engineering is a social discipline. Engineering work is situated within larger social, cultural, political, and environmental systems. These systems influence, and are influenced by, the processes and outcomes of engineering work (Kroes et al., 2006; Mosyjowski et al., 2020).

Thus, as described by NSPE: “An understanding of societal context is a critical aspect of most engineering activities.” (National Society of Professional Engineers, 2013, p. 16)

Engineering is a global discipline. Engineers are working in an increasingly globalized and interconnected world. Modern engineering teams may be dispersed across different countries (Kamp, 2016; National Academy of Engineering, 2004), and engineers may be developing products and systems for diverse global contexts (Wong, 2021). Engineering education is becoming increasingly globalized, leading to increased collaborations between engineers from different cultural traditions (Graham, 2018). The inputs and outputs of engineering work also have global implications, such as climate change (Intergovernmental Panel on Climate Change, 2021).

Lastly, **engineering (ideally) makes the world a better place**. Addressing societal needs is a core goal of engineering work (Accreditation Board for Engineering and Technology, 2022; National Society of Professional Engineers, 2013). Engineers, as part of their work, also regularly make ethical judgements that may have profound societal implications (Robison, 2021). As a result, engineers have a strong professional responsibility to apply their engineering knowledge for the benefit of society. Smith and Lucena (2021) have additionally emphasized that engineers have a responsibility to understand the broader structural conditions that marginalize and oppress certain stakeholder groups, and to use this contextual understanding to pursue equitable engineering outcomes.

While the eight themes about engineering work described above are grounded in prior literature and reflect the goals of modern engineering education, they are also in many ways aspirational rather than realistic representations of current engineering practice. For example, prior work has described various ways that engineering does *not* necessarily make the world a better place, including (but not limited to) racist algorithms (Benjamin, 2019) and environmental pollution (Washington, 2019). Sociotechnical aspects of engineering work also manifest differently in different professional contexts. For instance, Craps et al. (2022) solicited feedback from engineering practitioners and HR experts related to the core competencies needed for different engineering roles. They found that creative aspects of engineering work are applied and valued differently in product innovation engineering roles compared to process optimization roles. Articulating a clear and comprehensive vision of engineering as a sociotechnical discipline enables us to explore potential discrepancies between current engineering practice and theory/educational goals in greater depth.

2.3 Methods

2.3.1 Research questions

Our study sought to understand how engineering practitioners from various engineering industries conceptualized sociotechnical aspects of engineering work, as represented by the eight themes described in our background section. Our study was guided by the following research questions:

1. What sociotechnical aspects of engineering work do engineering practitioners feel align most and align least with their education and work experiences?
2. When interpreting their previous engineering experiences, how do engineering practitioners characterize engineering work and what it means to be an engineer?

2.3.2 Researcher positionality

Our research team was composed of three White women and two White men, representing a range of career levels and disciplinary perspectives. As educators of engineering students, our motivations for performing this work stemmed from our desire to transform engineering education to be more equitable and inclusive, in part by incorporating a stronger emphasis on the sociotechnical dimensions of engineering work. As part of this broader goal, we conducted the present study to better understand how engineering industry compares to the aspirational vision of engineering as a sociotechnical discipline outlined in our background section. This vision, while grounded in literature, is also a product of our ontologies, i.e., it reflects our own perceptions of, and aspirations for, the field of engineering based on our social identities and lived experiences. Thus, while we believe that the eight themes outlined in our background section represent a comprehensive accounting of the ways that engineering is a sociotechnical discipline, we also acknowledge that there are likely other ways to conceptualize the sociotechnical nature of engineering[5].

2.3.3 Participants

Twenty-eight engineering practitioners were recruited to participate in our study through the following methods: 1) study solicitation emails sent to alumni listservs, 2) study solicitation emails forwarded through personal networks, and 3) snowball sampling with study participants. Practitioner participants represented a variety of industries, undergraduate engineering majors, and educational backgrounds. Eighteen of our 28 participants reported identifying as White (non-Hispanic), five participants reported identifying as Asian American, two participants reported identifying as Black, two participants reported identifying as Hispanic (one White, one Native Hawaiian/Pacific Islander), and one participant reported identifying as multiracial. Fourteen of our 28 participants reported identifying as women, and fourteen reported identifying as men.

[5] For example, see (B. Cohen et al., 2014) for a liberal arts framing of engineering as a sociotechnical discipline.

Information related to our participants' experience levels, industries (self-reported), and educational backgrounds is reported in Table 2.1.

Table 2.1 Aggregate participant work and education information

Category	*n*	%
Total	28	100
*Industry**		
Automotive	11	39.3
Autonomous Vehicles	4	14.3
Software/Tech	4	14.3
Food & Beverage	4	14.3
Aerospace	3	10.7
Oil/Petroleum	2	7.1
Chemical	2	7.1
Medical Devices	1	3.6
Construction/Urban Development	1	3.6
Utilities	1	3.6
Robotics	1	3.6
Pharmaceuticals	1	3.6
Biotechnology	1	3.6
Years of Experience		
0-5	8	28.6
5-9	11	39.3
10-14	3	10.7
15-19	0	0.0
20-24	5	17.9
25+	1	3.6
*Undergraduate Major***		
Mechanical Engineering	13	46.4
Chemical Engineering	7	25.0
Electrical Engineering	2	7.1
Industrial and Operations Engineering	2	7.1
Computer Engineering	2	7.1
Civil Engineering	2	7.1
Aerospace Engineering	1	3.6
*Postgraduate Education****		
Engineering Master's	7	25.0
Business/Project Management Master's	5	17.9
None	17	60.7

*Nine participants indicated more than one industry
**One participant indicated more than one engineering undergraduate major
***One participant earned both an engineering master's degree and an MBA

2.3.4 Data collection

We conducted and audio-recorded a single 60 to 75-minute interview with each study participant. Eight participant interviews were conducted in person, while the remaining 20 interviews were conducted remotely over a video-conferencing software such as Skype or Zoom. During interviews, we provided participants with the following eight "statements about engineering work," based on the literature review described in our background section:

- Engineering is a technical discipline
- Engineering is constantly evolving
- Engineering is about synthesizing and integrating knowledge
- Engineering is a creative discipline
- Engineering is a team discipline
- Engineering is a social discipline
- Engineering is a global discipline
- Engineering makes the world a better place

As part of our interview protocol, we first stated that participants would be asked to select two statements about engineering work that aligned most with their education and work experiences. We then read out the eight statements listed above, and either handed each statement to participants on individual slips of paper (in person interviews) or sent the full list of eight statements to participants via chat function (remote interviews). We did not define our eight statements for participants. Instead, we encouraged participants to apply their own interpretations to these statements.

Once participants had selected two statements that aligned most with their experiences, we asked participants to describe a story, from their experiences, that related to each of their selected statements. As participants shared their two stories, we asked follow-up questions to clarify how participants interpreted each selected statement and connected each statement to their stories. At the conclusion of each story, we asked participants to describe what they learned from the experience about what it means to be an engineer.

During the second part of our interview, we asked participants to select two statements (from the original eight) that aligned least with their previous experiences. For each selected statement, we asked participants to describe why they felt that the statement aligned poorly. Participants were encouraged to provide a specific story related to each statement if they were able. We again asked follow-up questions to clarify how participants interpreted each selected statement and connected each statement to their experiences. No participant selected the same statement twice, i.e., no participant discussed ways that a statement both aligned most and aligned least with their experiences. Participants could also decline to choose statements that aligned least with their experiences, for instance because they felt that all eight statements aligned well. Four participants only selected one statement as aligning least, and one participant declined to select any statements that aligned least. Interview recordings were transcribed, and these transcriptions were checked for accuracy by a member of the research team.

2.3.5 Data analysis

To answer our first research question, we recorded and tallied the statements about engineering work that each participant selected as aligning most and aligning least with their education and work experiences.

To answer our second research question, we analyzed participants' interview responses to identify specific ways that participants described their engineering work and what it means to be an engineer in response to the eight statements that we provided.

First, two researchers reviewed the interview transcripts to familiarize themselves with the data. The two researchers identified representative quotes from participants' responses that captured how participants either 1) characterized their own engineering work or 2) characterized the work that engineers do in general. The two researchers then grouped together quotes that conveyed similar ideas about engineering work, as shown in Table 2.2. Schein (2016), in his framework for studying organizational cultures, has previously referred to ideas, assertions, or rationalizations that are shared across individuals as “beliefs.” We defined the central idea communicated by each group of participant quotes and, following Schein, titled these central ideas as “beliefs about engineering work.”

Table 2.2 Example of coding approach

Quotes from participants	Belief about engineering work
“*Bringing in people with different expertise, different backgrounds and even different day to day activities is usually important in making an effective and reliable product or process.*” (Participant 14, software engineer) “*There was also a lot of cross-functional teamwork. Not necessarily just working with your direct team, but working with other teams within the company. I've found in all of my roles that that's been extremely important.*” (Participant 15, automotive engineer)	Cross-functional collaborations across teams are more likely to develop successful engineering solutions than single engineers working alone

After defining an initial set of “beliefs about engineering work,” the two researchers reviewed participants’ responses again to identify additional quotes that had been missed during the initial round of review. These additional quotes were sorted into their corresponding beliefs. The two researchers also discussed their respective understandings of each belief and used these discussions to iterate on the definitions of each belief and the quotes sorted into each belief. The two researchers also combined groups of quotes in cases where the corresponding beliefs seemed overly similar, and split groups of quotes in cases where they felt it was important to capture nuances between beliefs. The two researchers also removed groups of quotes that ultimately did not seem to describe characteristics about engineering work or what it means to be an engineer. For example, two participants, in response to our eight statements, described how engineering companies do not provide adequate support for their employees. While this is an important point, it was also outside the scope of the present analysis. At the end of this grouping process, the two researchers had reached complete negotiated agreement as to 1) the list and definitions of beliefs represented in our data, 2) the number of participants that mentioned each belief, and 3) the statements about engineering work (both aligning most and aligning least) that elicited each belief.

Through our grouping process, we identified 71 different beliefs about engineering work that were described across participants[6]. Given the large number and diversity of identified beliefs, we thus chose to engage in an additional round of thematic sorting to identify key themes that applied across beliefs and could enable us to make broader inferences about participants' responses to our eight statements. For example, several beliefs seemed to relate to collaborative aspects of engineering work. We ultimately grouped these beliefs together under the broader theme "Engineering work requires collaboration."

The same two researchers who had engaged in the previous rounds of our analysis participated in the thematic sorting of identified beliefs. Each researcher performed their initial thematic sorting process individually, and then compared the themes that they had identified across beliefs. The two researchers discussed differences between their respective lists of themes, and together compiled a list of themes that incorporated both perspectives.

Lastly, we utilized an external audit to evaluate the trustworthiness of our thematic analysis (Leydens et al., 2004). As part of this audit, we recruited an external reviewer (paid, non-author) to complete their own thematic sorting of our list of 71 identified beliefs (with an anonymized example quote provided for each belief). Our external reviewer had prior experience performing qualitative analyses and was familiar with engineering education and work environments. After our reviewer had finished compiling their own initial list of themes, we showed them the list of themes that our research team had produced. We discussed and resolved

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[6] This number is relatively large in part because our participants had diverse experiences and we sought to preserve distinctions and nuances in participants' beliefs.

discrepancies between the themes identified by our team and the external reviewer, resulting in a final list of 15 themes. We also negotiated agreement as to the beliefs that were included within each theme. Each theme, on average, contained four to five beliefs. The main exception was the theme "Engineering work requires collaboration," which was well represented in our data and contained 15 different beliefs.

2.4 Findings

2.4.1 Statements about engineering work that aligned most and least with practitioner experiences (answering RQ1)

Table 2.3 summarizes participants' selections of statements about engineering work that aligned most and aligned least with their experiences. As a reminder, four participants selected only one statement that aligned least with their experiences, and one participant indicated that all statements aligned well.

Table 2.3 Summary of participant choices for statements about engineering work that aligned most and aligned least with their education and work experiences

Statement about Engineering Work (ABBR.)	Align Most	Align Least
Engineering is a team discipline (TEAM)	15	2
Engineering is about synthesizing and integrating knowledge (SYNT)	12	3
Engineering is a global discipline (GLOB)	7	7
Engineering is a technical discipline (TECH)	6	6
Engineering makes the world a better place (BETR)	5	9
Engineering is constantly evolving (EVOL)	5	12
Engineering is a creative discipline (CREV)	4	4
Engineering is a social discipline (SOCL)	2	7

Two statements were selected most often by participants as aligning *most* with their engineering experiences: "Engineering is a team discipline" (15/28 participants) and "Engineering is about synthesizing and integrating knowledge" (12/28 participants). The next most frequent statements selected by participants as aligning most with their experiences were "Engineering is a global discipline" (7/28 participants) and "Engineering is a technical discipline" (6/28 participants). The statements "Engineering makes the world a better place," (5/28 participants) "Engineering is a creative discipline" (4/28 participants) and "Engineering is a social discipline" (2/28 participants) were selected by low numbers of participants as aligning most with their experiences.

The statement "Engineering is constantly evolving" (12/28 participants) was chosen most often by participants as aligning *least* with their engineering experiences. The statements "Engineering makes the world a better place (9/28 participants), "Engineering is a global discipline" (7/28 participants), and "Engineering is a social discipline" (7/28 participants) were also chosen by at least a quarter of participants as aligning least with their experiences. "Engineering is a technical discipline" (6/28 participants), "Engineering is a creative discipline" (4/28 participants), "Engineering is about synthesizing and integrating knowledge" (3/28 participants), and "Engineering is a team discipline" (2/28 participants) were chosen by few participants.

2.4.2 Common beliefs discussed by practitioners related to statements about engineering work that aligned most and aligned least with their experiences (answering RQ2)

Our final list of themes, representing a summary of beliefs about engineering work that were discussed by participants, is provided in Table 2.4. These themes are organized in order of total prevalence ("Total" column). Table 2.4 also describes the number of participants who discussed each theme in the context of statements that aligned most with their experiences

(“Align Most” column) compared to statements that aligned least with their experiences (“Align Least” column).

Table 2.4 Thematic summary of beliefs about engineering work described by participants

Theme	Participants (out of 28)			Definition
	Total	Align Most	Align Least	
Engineering work requires collaboration	25	23	12	Teamwork is a core aspect of engineering work. Engineers must be effective collaborators to complete their work successfully.
Engineering work requires technical competency	24	23	10	Engineers are defined by their ability to apply technical knowledge to solve a diverse array of problems.
Engineering work requires communication	23	19	7	Communication is a core aspect of engineering work. Engineers must be effective communicators to complete their work successfully.
Engineering work impacts society	22	19	13	Engineering work impacts stakeholders and broader society. Engineers should account for societal impacts and context.
Engineering work affected by constraints	13	10	8	Engineers regularly navigate constraints such as time or budget as part of their engineering work.
Context of engineering work is changing	12	9	4	Societal needs and available technologies both change over time. Consequently, engineers must constantly learn new skills to complete their work.
Engineering work is open-ended and iterative	12	10	4	Engineering work rarely involves predetermined “right” answers or definitive stopping points. Iteration and open-ended exploration are core aspects of engineering work.
Personal values influence engineering work	11	3	10	Engineering work and outcomes are not value neutral, but rather are influenced by the personal values and priorities of individual engineers and/or companies.
Engineering knowledge is consistent	11	2	10	Core engineering knowledge has remained largely the same over time and across cultures.
Sociocultural context influences engineering work	10	7	3	Engineering work processes differ across geographic regions, for instance due to differences in culture or regulations.
Engineering work is convergent-leaning	10	4	8	Engineers tend towards adopting prior solutions, or otherwise feel pressured to follow predetermined work processes with limited room for creativity.
Barriers to collaborative engineering work	10	7	3	Engineers encounter a variety of barriers that prevent them from collaborating successfully with other engineers, including personality differences or work environments that discourage teamwork.
Scope of engineering work is limited	9	4	7	Aspects of engineering work environments, such as siloing, can constrain engineers’ abilities to conceptualize the broader contexts or impacts of their engineering work.
Engineering work teaches necessary skills	5	2	4	Due to differences between engineering education and work, engineers usually learn the skills that they need to complete their jobs once they enter industry.

Interpersonal is separate from engineering work	4	0	4	Social bonding is unrelated to effective collaboration in engineering contexts.

The following sub-sections, organized by theme, present a selection of common beliefs about engineering work that participants discussed in the context of statements that they selected as aligning most and least with their engineering experiences.

Engineering work requires collaboration. Twenty-five out of 28 participants discussed beliefs about collaborative aspects of engineering work and the collaboration skills that engineers need to perform their work successfully. Participants mainly discussed beliefs about collaborative engineering work in the context of statements that aligned *most* with their experiences, particularly the statements "Engineering is a team discipline" (15 participants) and "Engineering is about synthesizing and integrating knowledge" (eight participants). A summary of participants' responses aligning with the theme "Engineering work requires collaboration" is provided in Table 2.5.

Table 2.5 Number of participants, per statement about engineering work, that discussed beliefs about collaborative aspects of engineering work (total = 25 participants)

		Statement about engineering work							
		TEAM	SYNT	GLOB	TECH	BETR	EVOL	CREV	SOCL
# of participants	Align most	15	8	2	1	2	2	3	1
	Align least	2	1	1	4	0	0	1	3

Participants described several beliefs about the nature and purpose of professional engineering teams. For example, 13 participants described how cross-functional collaborations between individuals with different professional roles were an essential component of their engineering work. In the words of one participant, who identified as having six total years of engineering experience working in the food & beverage and aerospace industries:

"*There's nothing that I could do solely on my own to change a process or make something better. It was always working with the mechanics, working with different engineers that could actually change the work procedures and approve the changes to make sure that everything still worked together. I think in general at [Engineering Company], one tiny change seems like it would be no big deal, but you actually have to have 15 different groups touch it and make sure that everyone is on the same page because there's so much stuff working together to make things happen in that factory. It was very much a team discipline and very cross functional.*" (Participant 26)

As described by this participant, engineers in a professional engineering context may work with a variety of individuals occupying a diverse array of job roles to complete their engineering work. These cross-functional teams may include a great number of people (e.g., 15 different groups), all of whom may need to be consulted regarding potential design changes. Eight participants further asserted that engineers work in teams as part of their engineering work because typical engineering systems are too large and complex for an individual person to know all the relevant details. For instance:

"*'Engineering is a team discipline.' I interpret that [statement] as being that engineers rarely work by themselves. They rarely own all the expertise associated with an engineered product, whether it be a bridge being built or a chemical process. The idea is you have to know your role and your level of expertise very well, and work within teams constantly.*" (Participant 1)

According to this participant, who identified as having 23 years of experience working in the oil industry, the cross-functional nature of professional engineering teams is necessitated in part by the complex nature of modern engineering products such as bridges or chemical processes. The successful development of these products requires the input of many individuals who each possess highly specialized knowledge.

Another belief, described by nine participants, was that engineering teams comprising diverse perspectives (due to differences in educational backgrounds and/or personal experiences) are more likely to develop successful engineering solutions than single engineers working alone. According to one participant, who identified as a software engineer with three years of professional experience:

"*Everybody has their own set of experiences, even if you have multiple people from the exact same background, they each have their own experience… Having more people involved helps, if not eliminate [your] biases, at least average them. If you have one person who is biased toward this thing, one person who is biased towards this other thing, they kind of on average give a thorough investigation of what could go wrong.*" (Participant 14)

In other words, each engineer has their own set of "biases" based on their previous experiences. By combining the different perspectives of team members, engineering teams can perform more comprehensive investigations of potential solutions and/or failure modes.

Participants, especially those with experience working in the automotive industry, also asserted that engineers need certain skills to collaborate effectively. For instance, nine participants indicated that engineers should try to understand teammates' perspectives and priorities and adapt their collaboration styles to ensure effective interactions. As described by one participant, who identified as having seven total years of experience working in the automotive, aerospace, and tech industries:

"*You have to learn the language and what's important. I did my own approach several times… and that was very ineffective because it was speaking a different language than [the other engineers] were used to. What was important was usually working with someone that [the other engineers] had previous experience with, someone they trusted from a technical side, and then validating with them beforehand. They would suggest, 'Hey, use this template or this format,' or 'Learn to speak in this certain perspective,' and that was important to gain alignment on.*" (Participant 17)

In other words, engineers need to "learn the language" of their co-workers to be able to collaborate effectively. As suggested by this participant, more senior co-workers can be a useful resource for learning this language.

Relatedly, eight participants emphasized that successful engineers require general interpersonal skills beyond just technical knowledge. One participant, who identified as an automotive engineer with 26 years of experience, expressed this belief as follows:

"*That's where the teamwork and the verbal skills, the communication skills become so important. You can be the most brilliant and gifted engineer, but if you're not able to work well with others and easily communicate, draw information from them and present it in an easily understood* *manner… then you'll be hamstrung the rest of your life… It's really easy to step on people's toes, and you spend weeks overcoming the damage you've done from a small mistake that offended somebody.*" (Participant 19)

As described by this participant, even engineers who have strong technical backgrounds may struggle to be successful in their work unless they also have strong teamwork and communication skills that enable them to collaborate effectively. Eight participants also described a similar belief that engineers who have strong interpersonal relationships with their team members perform more effective engineering work. For example:

"*When I worked with teams, worked with subcontractors that were good team players, I think we just really tried to make it work at whatever cost… It was just understood that everybody's on the same team with the same common goal. When we're working with a subcontractor that didn't care, they were more inclined to ... They didn't care about the schedule. They just didn't care at all. They were willing to let the project fail because their feelings were hurt. It was just really upsetting… When you find people that are set on a common goal, willing to figure things out, willing to ask me for help, knowing that I might know something more than they did, and I'm willing to ask questions ... Engineering has to be a group effort.*" (Participant 13)

As described by this participant, who identified as having two years of experience working in construction and urban development, the interpersonal relationships that engineers develop with their teammates (in this case, sub-contractors) are very important. Engineering work is highly collaborative, and teammates with positive interpersonal relationships are more likely to rely on each other for help and devote their efforts to achieving a common goal.

Engineering work requires communication. Twenty-three out of 28 total participants discussed beliefs related to the role of communication in engineering work. These beliefs were often related to participants' beliefs about collaborative work (as highlighted in the above quote from Participant 19) but placed a greater emphasis on the skills that engineers need to exchange information effectively. Participants primarily discussed beliefs about communication in the context of statements that aligned *most* with their experiences, particularly the statements "Engineering is a team discipline" (10 participants) and "Engineering is about synthesizing and integrating knowledge" (seven participants). A summary of participants' responses aligning with the theme "Engineering work requires communication" is provided in Table 2.6.

Table 2.6 Number of participants, per statement about engineering work, that discussed beliefs about communication in engineering work (total = 23 participants)

		Statement about engineering work							
		TEAM	SYNT	GLOB	TECH	BETR	EVOL	CREV	SOCL
# of participants	Align most	10	7	3	4	1	3	0	0
	Align least	1	0	1	3	0	1	1	1

Fourteen participants (including seven of 11 participants with experience as automotive engineers) asserted that engineers must be able to communicate technical knowledge to teammates, project collaborators, and/or managers as part of their engineering work. In the words of one participant, who identified as an automotive engineer with 10 years of experience:

"*I think in school we laugh about how engineers can't communicate well and hate talking and writing, but it's actually really, really important… especially people who like to be more* *introverted and think about science and stuff, it's hard to put yourself out there and maybe you're scared of being wrong. But I think that's the only way sometimes you get to the bottom of problems is by actually saying something and being wrong and then someone can correct you.*" (Participant 2)

As described by this participant, it is important for engineers to communicate information to their co-workers, even if they are afraid of being wrong. Communication is important both for checking personal knowledge and assumptions, and for facilitating problem-solving. Eight participants also indicated that engineers should be able to communicate technical information with project stakeholders, such as customers, as part of their engineering work. As described by one participant, who identified as a software engineer with 21 years of experience:

"*It's a team environment, in terms of the different people bring different skillsets, and no one person can do it all… One of my other [co-workers]… is very clinical in her expertise. She can actually go to a clinical site, talk to a doctor, and be able to bring that input in and say, 'Well, this is how the doctors or the technicians out in the field are going to use our software… This is how we need to test it, because this is what they're going to do.' Sometimes if you get too much of the technical expertise, you end up with something that's very... It does this, this and this, but [you] didn't ever think how somebody else might use it, right?*" (Participant 9)

Thus, according to this participant, the ability to communicate with customers (in this case, clinicians) can enable engineers to gather specific information about realistic use cases. This information, in turn, can guide engineers' product development processes.

Participants, particularly in the context of the statement “Engineering is about synthesizing and integrating knowledge,” also highlighted the importance of communication skills for gathering information. For example, nine participants (including all four participants with experience in food and beverage manufacturing) described how they needed to communicate with and learn from people representing diverse job functions within their companies to inform their engineering work. One participant, who identified as having seven years of experience working in the food & beverage industry, expressed this belief as follows:

“*[Engineering] is all about your approach to solving problems and your ability to bring people together and extract information that allows the problem to be solved… I get pulled in a lot to lead root cause events and different things like that where we're trying to ... everyone has a little bit of the knowledge about what happened, being that piece to synthesize it together and using what I know about it to ask the right questions and dig in in the right spots and knowing enough to know how to start and where ... at least knowing the basic layout of the process and stuff to then get them to help fill in the detail, but it's really just about giving a broad basic knowledge and building on that with the problem-solving and facilitation skills.*” (Participant 23)

This participant described how a core aspect of her engineering job involved asking the right questions of co-workers to gather information that could inform her problem-solving process. This information was usually distributed across individuals, meaning that this participant typically needed to gather and synthesize information from multiple coworkers. While Participant 23 discussed the need to synthesize information for her own use, five other participants indicated that engineers should be able to synthesize technical information into key points that can be clearly communicated to others. In the words of one participant, who identified as having four total years of experience in the autonomous vehicle and robotics industries:

"*And so the experience of having all this information dumped on top of me and then having to make sense of it kind of taught me more than almost anything else that as an engineer, it is the ability not only to know things… but to take as inputs an incredible quantity of data and synthesize it into something meaningful and useful, presentable that you can tell a superior or someone who is asking a question... Something as simple and open-ended, both simple and complicated as the question 'what happened?,'*" (Participant 5)

Thus, according to this participant, the communication of technical information is fundamentally an act of synthesis. Engineers gather information from a variety of sources, and then figure out which aspects of that information are relevant and important to share.

Engineering work requires technical competency. Twenty-four out of 28 participants discussed beliefs about the technical knowledge and skills that engineers apply to perform their engineering work. Participants mainly discussed beliefs about technical engineering competencies in the context of statements that aligned *most* with their experiences, particularly the statements "Engineering is about synthesizing and integrating knowledge" (ten participants), "Engineering is a team discipline" (seven participants), and "Engineering is a technical discipline" (five participants). A summary of participants' responses aligning with the theme "Engineering work requires technical competency" is provided in Table 2.7.

Table 2.7 Number of participants, per statement about engineering work, that discussed beliefs about technical competencies in engineering work (total = 23 participants)

		Statement about engineering work							
		TEAM	SYNT	GLOB	TECH	BETR	EVOL	CREV	SOCL
# of participants	Align most	7	10	3	5	1	0	4	0
	Align least	0	1	0	2	0	5	1	1

Thirteen participants (including six of 11 participants with experience as automotive engineers) asserted that engineers need to understand how their work affects and is affected by other relevant components, processes, and systems. In the words of one participant, who identified as having 22 years of experience in the automotive and autonomous vehicles industries:

"*As the vehicle starts to come to life, it's kind of going from coarse to fine with all of the inputs and information and keeping it on a path. My job [as chief engineer] was to take all those inputs, distill it, and continue it on a path that brings it to its launch at the right time. And that can be anything from making a specific aesthetic work, and helping the engineering team get there, to packaging decisions that need to be made in the vehicle, to get all the systems to integrate. And then the performance integration of how the characteristics of the vehicle will come together. So ride and handling, noise and vibration, all of that kind of stuff.*" (Participant 6)

As suggested by this participant, subsystem integration and subcomponent packaging are important considerations than can affect the success of engineering products. These integrative factors were especially salient for Participant 6 due to their role as a chief engineer.

Eight participants, particularly in the context of "Engineering is a technical discipline," indicated that technical engineering knowledge is necessary for engineers to develop comprehensive understandings of their engineering work. As described by Participant 1, who was previously introduced as an engineer with 23 years of experience in the oil industry:

"'*Engineering is a technical discipline.' The way I interpret that [statement] is that the interpersonal relationships are very important, but underneath, everything has to be solid technical foundations. And in many places, the engineer is very heavily relied on, probably more than they appreciate, to be the judge of what's true and what's not true. And that gets very deeply into technical aspects.*" (Participant 1)

In discussing how engineers judge "what's true and what's not true," this participant was referring to how engineers apply their technical knowledge to troubleshoot problems and identify viable solutions. While this participant felt that the interpersonal aspects of engineering work were certainly important, they also described the foundations of engineering work as being fundamentally technical. Six participants (including all four participants with experience working in food and beverage manufacturing), similarly described how engineers leverage their previous technical knowledge and project experiences to inform their engineering work. Participants mainly discussed this belief in the context of "Engineering is about synthesizing and integrating knowledge." For example:

"*A current project I'm working on, we are taking our preventative maintenance… We had a third party contractor come in and tell us we do too much, too often. So we're trying to look at our system and make it better. A lot of this is seeking knowledge and experiences I have learned already, through my experiences, and evaluating the tasks that we are doing, which to me is* *integrating the knowledge that I have. I'm also working with our subject matter experts and leaning on their knowledge to try and make decisions that are not 'data' based, more from experiences and recollections of the crew.*" (Participant 25)

In this case, Participant 25, who identified as having eight years of experience working in the food & beverage industry, relied on their prior knowledge and experiences, as well as those of their co-workers, to revise the maintenance plan for their company's assembly line. Seven participants also described the role of engineering education in helping engineers develop their technical knowledge. Specifically, participants indicated that engineering education teaches engineers processes, mindsets, and fundamental knowledge that are applicable across a wide variety of problems. In the words of one participant, who identified as a software engineer with nine years of experience:

"*When I was in college, we only learned C++ and the professors would just teach us… the fundamental things for loops, how to create a class, but they never really mentioned how these things connect with the real world… I was like, 'This doesn't seem to help me at all with my job function.' But then as I started going deeper and deeper into the job, I realized that it's exactly those fundamentals that really get your head rolling to... It becomes my job to match it with the job description… so that I could now understand what I have to do for work. Engineering definitely is a process in which you learn a core set of fundamentals, but that's the basic tools that get you to the advanced things.*" (Participant 22)

In other words, this participant felt that their engineering education provided fundamental knowledge that ultimately enabled them to perform their engineering work. As part of this fundamental knowledge, eight participants described how engineering involves a distinct and foundational problem-solving process that is applicable across contexts. One participant, who identified as an automotive engineer with 6.5 years of experience, expressed this belief as follows:

"*It's all about the process, right?... Let's define what the problem is. Let's work through all our avenues to try and understand what the problem is. Figure out the root cause. Come up with a solution, get that solution implemented, and then we can figure out why it went wrong, how we prevent it in the future.*" (Participant 20)

This participant identified key aspects of engineering problem-solving processes, including problem definition, root cause analysis, and solution ideation. As suggested by our participants, the ability to apply these problem-solving steps is part of what makes one an engineer.

Engineering work impacts society. Twenty-two out of 28 participants discussed beliefs about the societal contexts and impacts of engineering work. These beliefs occurred in a variety of contexts. For instance, four participants discussed societal contexts and impacts because "Engineering makes the world a better place" aligned *most* with their experiences. Meanwhile six other participants discussed societal contexts and impacts because this statement did *not* align with their experiences. Furthermore, six participants discussed societal contexts and impacts because "Engineering is a global discipline" aligned *most* with their experiences. A summary of participants' responses aligning with the theme "Engineering work impacts society" is provided in Table 2.8.

Table 2.8 Number of participants, per statement about engineering work, that discussed beliefs about social impacts of engineering work (total = 22 participants)

		Statement about engineering work							
		TEAM	SYNT	GLOB	TECH	BETR	EVOL	CREV	SOCL
# of participants	Align most	4	3	6	2	4	2	2	2
	Align least	0	0	2	1	6	1	0	4

Participants discussed beliefs about the broader societal impacts of engineering work and the consequent responsibilities of engineers. For instance, nine participants indicated that the goal of engineering work is to improve society. For example:

"*Engineering is looking to solve very specific problems… no matter what industry it's in. It's always targeted. There's always a need and engineering is meant to fill a need or improve something that is lacking in some way or something that could be more efficient or could be improved. I feel like engineering is a way to address a problem that is meant to improve either the way someone is able to function in the world or directly influenced their life.*" (Participant 12)

According to this participant, who identified as having 22 years of experience working in the medical device industry, engineering is fundamentally about addressing societal needs and/or improving processes. Ten participants further asserted that engineers should account for the broader social, environmental, and/or economic implications of their engineering work. As described by one participant, who identified as having 20 total years of experience across multiple industries including pharmaceuticals and biotechnology:

"*After I would be briefed on that [by marketing]… the first thing I think about as an engineer is the type of material, the design, the color, what impacts it? Who produces it, the safety, all those things would hit me right away... To me, this is the greatest example of [engineering] being a 'global' discipline because while this [product] satisfies a health need, it also satisfies a monetary need for the company to be able to put out a nice, cute bottle that someone would be attracted to. It's all about engineering, completely in all aspects… how you access the product, how you carry the product, and how you are able to move around with the product. There's ergonomics in there, there's ergonomic engineering, there's functional engineering, there's delivery engineering, all of that is built into it.*" (Participant 28)

In this example, Participant 28 emphasized several considerations related to the design of their consumer product, in this case a bottle. The goal of the product was to support consumer health, while also making the company money. The product also needed to be ergonomic and accessible. This participant thus felt that engineering was a "global discipline" because, based on her various experiences and as demonstrated in the above example, the technical design of engineering products strongly influenced, and was influenced by, broader societal contexts.

Seven participants suggested that engineers, due to the potential societal implications of engineering work, have a responsibility to use their knowledge and positions for the betterment of society. In the words of one participant, who identified as an automotive engineer with two years of experience:

"*Even if I know the organization as a whole doesn't really care… it's up to you to put in the effort to make the small change that you think can make a big difference… If it matters to you to make a world a better place, you have to find a way, whether it's volunteering outside of what you do now. If your job can help someone, doing a better job to make sure that you are making a difference.*" (Participant 18)

According to this participant, engineers have a responsibility to work towards the betterment of society even if the company that they work for seems indifferent. For engineers, that societal responsibility might involve being diligent in their engineering work and thinking comprehensively about potential impacts or volunteering outside of work to make the world a better place.

Participants also discussed beliefs related to the users of their technologies. Eleven participants asserted that engineers should gather information about users and use context to inform their engineering work. As described by one participant who identified as an automotive engineer with 11 years of experience:

"*You either meet the [customer] requirements or you don't meet the requirements. There's really no in-between. So making sure that whatever we do upfront from understanding how the customer will use the vehicle, making sure that divulges down to our level, to a component level, to understand if the components are either good or they're bad… [Our product has] such a broad range of users. You have people who go mudding or you'll have people who are using it on a farm and ranch. You can imagine those duty cycles are very different for those components* *depending on what you're doing with them. We'll usually set those requirements based on the product. [Marketing] teams will provide that down to us. They collect that data from surveys and looking at older parts that we had returned [through warranty].*" (Participant 27)

In other words, this participant indicated that the success of engineering products depends upon how well they meet users' requirements, which are established through information gathered from users and/or prior products. This participant also acknowledged that user requirements should account for a wide range of potential use contexts. Related to this point, seven participants, related to the statement "Engineering is a global discipline," further specified that the use contexts for engineered products typically change across different global regions. As a result, engineers must account for regional variations as part of their engineering work. In the words of one participant, who identified as having seven total years of experience working in the automotive and oil industries:

"*We also worked closely with the supplier of the tracking devices, and they were out of Singapore, so there was a lot of global knowledge-sharing. We were able to share best practices for each region, and it was very interesting to see the different constraints that we would run into in maybe a swampy area in Malaysia, Indonesia versus the desert in the Middle East versus the jungles of South America. We were all trying to do the same thing, but we were running into a lot of different constraints.*" (Participant 16)

While this participant specifically noted how environmental and climate contexts influenced technological constraints, other participants pointed to differences in infrastructure, language, and cultural norms as influencing technical outcomes as well.

Other notable beliefs about engineering work. Beyond the four themes discussed in the previous sub-sections, there were other beliefs that were notable because they seemed to represent the primary reason that participants selected specific statements as aligning most or least with their experiences. For example, 10 participants selected the statement "Engineering is constantly evolving" as aligning *least* with their experiences. All 10 of these participants justified their selection by suggesting that the foundational knowledge, tools, and problem-solving processes used to perform engineering work have remained largely the same since their initial discovery. In the words of Participant 2, previously introduced as an automotive engineer with 10 years of experience:

"*I don't think the approaches changed to problem solving, it's just the technology that's available changes a little bit and you think you can do more. But a lot of times you're still basing it on the same fundamental things that people have always been doing. You learn more and you think of some new ways to approach it maybe, but it's still using the same principles.*" (Participant 2)

Thus, according to this participant, while the technologies that engineers may be working on are constantly evolving, the actual problem-solving approaches and scientific principles used to create those technologies have remained fundamentally the same over time.

Eight participants selected "Engineering makes the world a better place" as aligning *least* with their experiences. Six of those participants justified their selection in part by emphasizing that engineers have different personal values, and that these values influence the outcomes of their work. As described by one participant, who identified as having two years of experience working with autonomous vehicles:

"*Engineering itself is not a natively good or bad discipline. I think that it is very much, how it is applied could be horrific or incredible and to some extent it's in the eye of the beholder. But keeping wise to the fact that it can make the world a much, much worse place, and there's certainly plenty of examples of that.*" (Participant 8)

In other words, Participant 8 felt that engineering could produce either good or bad outcomes depending upon the values of the engineer. In particular, they referred to several examples of engineering work leading to what they perceived to be negative societal outcomes. Four participants (all automotive engineers) described a related belief that pertained specifically to engineering companies. These four participants felt that engineering companies prioritize increasing their bottom line over improving society or protecting the environment, and thus only work towards positive societal outcomes if they are profitable.

Seven participants selected "Engineering is a global discipline" as aligning *most* with their experiences. Five of those participants justified their selection in part by describing how engineering work processes may vary based on culture, meaning that engineers should be cognizant of potential cultural differences in their international collaborations. One participant, who identified as having three years of experience working in the automotive and aerospace industries, expressed this belief as follows:

"*You definitely have to be adaptable and patient… You can't assume everyone has an American work perspective. The Japanese have very different decision-making practices. It's more like you have to defer to people who are higher up than you. You do that in America too, but it's usually like they'll assume you're the expert and listen to what you say. But in Japan, it's more like everybody needs to be onboard and agree.*" (Participant 11)

This participant highlighted key differences, such as deference to authority and communal decision-making, that based on their previous experiences seemed to characterize Japanese work cultures more so than American work cultures. According to this participant, an American engineer working with a Japanese company should be aware of these differences and adapt their collaboration styles to suit their international colleagues.

2.5 Discussion: Practicing engineers' perspectives of their engineering work

We developed eight statements, grounded in literature, that together described an aspirational vision of engineering as a sociotechnical discipline. We then interviewed 28 engineering practitioners about which of our eight statements, based on their own interpretations, aligned most and aligned least with their engineering experiences. While our practitioner participants were all working mainly in American, corporate engineering contexts, they represented a range of engineering industries and educational backgrounds. Our findings highlight aspects of our participants' engineering experiences that they have thus far found to be most salient, related to the statements we provided.

Fifteen out of 28 participants selected "Engineering is a team discipline" as a statement that aligned most with their engineering experiences. Overall, 25 total participants discussed the important role that collaborative activities and skills played in their engineering work, and twenty-three participants emphasized the importance of communication activities and skills. Our findings align with previous descriptions of engineering work as being highly collaborative and involving extensive communication across individuals (Anderson et al., 2010; Trevelyan, 2010).

A consistent point that emerged across participants' responses was that collaboration and communication in engineering work is necessitated by the complex nature of modern engineering projects, with relevant engineering expertise often distributed across many individuals or sub-teams. Our participants' understandings of engineering work thus generally aligned with Trevelyan's (2010, p. 175) characterization of engineering practice as "distributed expertise enacted through social interactions." In part, the prevalence of this theme in our data may have stemmed from the work contexts of our participants, since several of our participants worked in large-scale, corporate industries. Jesiek et al. (2021), in their study of early career engineers at large manufacturing companies, similarly found their participants frequently communicated and collaborated across social, geographic, organizational, and disciplinary boundaries as part of their engineering work.

We also found that several participants emphasized the importance of interpersonal skills for engineering work. Participants described these skills as necessary for communicating and collaborating effectively with co-workers and suppliers. Our participants' emphasis on interpersonal skills as a core engineering competency aligns with prior studies of professional engineering practice. For example, Anderson et al. (2010) interviewed and observed "effective" engineers at six American engineering firms. Their participants consistently cited "communication" as their most important skill. Their participants also discussed the importance of being a good "team player," which aligns with our participants' discussions related to the importance of positive interpersonal relationships with coworkers.

Twenty-four out of 28 participants discussed the technical knowledge and skills that engineers employ when performing engineering work. However, only six participants selected "Engineering is a technical discipline" as a statement that aligned most with their experiences. Participants mainly discussed technical competencies in the context of the statement "Engineering is about synthesizing and integrating knowledge." Related to this latter statement, participants often referred to characteristic ways that engineers learn and apply technical knowledge to solve engineering problems. For example, participants described how engineers need to understand the interrelationships between different components and processes involved in the development of engineering products. This mindset represents a core aspect of "engineering systems thinking," as defined by Frank (2000). Participants also discussed how engineers leverage experiential knowledge and utilize a distinct and well-defined problem-solving process. Prior studies of engineering practice have similarly described how engineering practitioners seem to follow a specific engineering problem-solving process involving problem discovery and investigation, root cause analysis, and evaluation and communication of potential solutions (Itabashi-Campbell & Gluesing, 2013; Trevelyan, 2010).

Related to the topic of engineering knowledge, ten out of 28 participants indicated that the statement "engineering is constantly evolving" did not align well with their experiences because, from their perspectives, core engineering knowledge has not changed much over time. These participants clarified that the *products* of engineering work were constantly evolving, but not the problem-solving processes and/or scientific principles that enabled this work to be performed. Our participants' conceptions of engineering work thus highlight an interesting tension. On one hand, the National Academy of Engineering (2018), in a recent report, described several ways that the field of engineering has evolved over time. Core engineering knowledge has expanded to include computing and social sciences, and engineers are increasingly working on projects that center sustainability and societal impacts. However, our findings suggest that these recent evolutions, on their own, may not challenge engineers' fundamental conceptions of engineering work. For instance, engineers may perceive the social sciences to be an additional body of knowledge that can simply be integrated, along with math and physics knowledge, into "standard" engineering problem-solving approaches[7]. The belief that core engineering knowledge is largely unchanging also implicitly positions such knowledge as "objective" and "unbiased," (Cech, 2013) which is at odds with substantial evidence that the production of scientific knowledge (in the US/Europe) has historically been and continues to be racist (McGee, 2020), sexist (Harding, 2006), ableist (Linton, 1998), etc.

Twenty-two out of 28 participants discussed societal impacts of engineering work and the need for engineers to account for these impacts as part of their work. The main statement that elicited discussions of societal impacts was "Engineering makes the world a better place," which was selected by five participants as aligning most with their experiences and nine participants as aligning least. A common critique of this statement by our participants was that engineering work, particularly in a corporate context, does not always produce positive societal outcomes. Rather, participants suggested that engineering work could have positive or negative outcomes depending upon the personal values or priorities of engineers and/or companies. In general, participants seemed to position ethical considerations and responsibilities[8] as central to engineering work. However, as argued by Baillie and Levine (2013), a commitment to *ethical* engineering work does not necessarily imply a commitment to *just* engineering work that reduces

[7] This may represent an overly idealistic scenario, given how, in practice, engineers often perceive social science knowledge as less "rigorous" and thus less valuable than math and science knowledge. See (Riley, 2017)
[8] For instance, as described by (Robison, 2021)

societal inequities. Put another way, it was unclear to what extent our participants, in their critiques of the statement “Engineering makes the world a better place,” were also critiquing dominant discourses in engineering, such as the belief that engineering work should be separate from “political” concerns such as diversity, equity, and social justice (Baillie & Levine, 2013; Cech, 2013).

The societal impacts and contexts of engineering work were also discussed by participants who selected the statement “Engineering is a global discipline” as aligning most or least with their experiences. In particular, participants emphasized that engineers need to account for differences in regional use cases that may result from environmental, political, and/or cultural differences. Participants also described how engineering work processes are influenced by local cultural norms and regulations. Our participants’ perspectives thus align with observations from Trevelyan (2013) who, in their comparison of Australian and South Asian engineering practices, found that engineering work is highly influenced by local social, economic, cultural, and political factors. Only six participants discussed societal impacts related the statement “Engineering is a social discipline” (two align most, four align least). Since this statement was selected only nine times overall, it is difficult to draw conclusions as to why participants more consistently selected the statements “Engineering makes the world a better place” and “Engineering is a global discipline” to discuss societal implications of engineering work.

The statement “Engineering is a creative discipline” was selected by only eight participants overall (four align most, four align least). It is unclear why this statement elicited few strong reactions from participants. For example, participants typically did not challenge this statement as a descriptor of engineering work. Of the participants who struggled to select statements that aligned least with their experiences, only one ultimately selected “Engineering is a creative discipline." At the same time, few participants explicitly discussed creative aspects of engineering work, although 12 participants did generally acknowledge that engineering work involves iterative and open-ended problem-solving. Ultimately, our study design, in restricting the number of statements that participants could select as aligning most and aligning least with their experiences, encouraged participants to focus on engineering experiences that were most salient for them. As such, our findings may simply indicate that creative aspects of engineering work, such as identifying novel solution possibilities or drawing unique conclusions from available data (Kamp, 2016), were potentially present in our participants' experiences but were not as salient as other common work activities such as collaborating and communicating with co-workers or integrating technical knowledge.

2.5.1 Limitations

Our findings do not represent a comprehensive accounting of our participants' engineering experiences. Our participants may have possessed other beliefs about engineering work that they did not mention due to constraints imposed by our interview protocol. For example, participants may have possessed beliefs about engineering work that they felt were unrelated to our eight statements. Participants were also only allowed to select two statements that aligned most with their experiences and two statements that aligned least. Participants may have possessed additional beliefs that did not pertain to the statements they selected.

The perspectives of early-career engineers working in corporate-industrial contexts (such as automotive engineering) were also highly represented in our data. Participants with these backgrounds represented a high proportion of our overall sample because they were readily accessible to us through personal and university connections. There is a precedent for studying engineering practice in the context of corporate-industrial contexts (e.g., Jesiek et al., 2021).

However, more work is needed to determine how well the practitioner perspectives described in this study align with those of engineers with other career backgrounds. Furthermore, 18 of our 28 participants reported White (non-Hispanic) as their racial identity. A different participant sample, featuring a higher proportion of engineers of color, would likely describe different beliefs about engineering work.

Lastly, we recognize that there are several ways to interpret our data. The findings presented in our paper reflect participant perspectives and experiences that were most recognizable to the two researchers who led our data analysis (first and third author). The points emphasized in our discussion section reflect our unique perspectives and critiques of the field of engineering. Furthermore, our study design followed traditional (i.e., White, Eurocentric) norms in qualitative research (e.g., Creswell & Plano Clark, 2018; Patton, 2015). A different research team, employing a more participatory research approach (e.g., Bradbury et al., 2019; Stewart, 2021), would elicit different types of perspectives from participants, and thus might report different findings as well.

2.6 Conclusion

Our study explored engineering practitioners' perspectives on engineering as a sociotechnical discipline using eight statements synthesized from literature: "Engineering is a technical discipline;" "Engineering is constantly evolving;" "Engineering is about synthesizing and integrating knowledge;" "Engineering is a creative discipline;" "Engineering is a team discipline;" "Engineering is a social discipline;" "Engineering is a global discipline;" and "Engineering makes the world a better place." We found that collaborative and technical-integrative aspects of engineering work were highly salient for our participants. However, several participants, based on their experiences, challenged the ideas that engineering (specifically, engineering knowledge) is constantly evolving and that engineering makes the world a better place. In addition, few participants discussed creative aspects of engineering work, perhaps indicating that these aspects were less salient for our participants. Our findings highlight specific ways that our participants' engineering work, based on their own perceptions, did not seem to align with the aspirational vision of engineering as a sociotechnical discipline reflected in our eight statements.

Our findings have implications for engineering education and practice. For example, participants developed their perspectives on engineering work in part through their educational experiences. Engineering educators, to support engineering students in developing robust conceptions of engineering as a sociotechnical discipline, might emphasize how 1) the field of engineering is constantly evolving, 2) engineering can serve the common good, and 3) engineering work is creative. However, even with changes to engineering education, our findings suggest that engineering work practices may still limit the ways that engineers engage with sociotechnical aspects of engineering beyond teamwork. Our findings thus suggest that a culture shift in engineering may be needed to achieve the aspirational vision of engineering as a sociotechnical discipline described in this paper. Such a culture shift might include transitioning towards engineering projects that center societal impact, fostering the creative acumen of engineers, and building inclusive work environments that support the full participation of engineers with diverse identities and backgrounds.

In closing, it is important to note that the aspirational vision of engineering as a sociotechnical discipline presented in this paper is ultimately not that aspirational. While it reflects the current goals of engineering education, it also leaves out important points. For instance, we did not include a statement in our study explicitly related to the idea that engineering work should be justice-centered and transformative; these characteristics are needed for engineering work to serve the needs of society as a whole, rather than a privileged minority(Baillie, 2021; Riley, 2008). Thus, while our study highlights important tensions in the ways that sociotechnical aspects of engineering work may manifest in current engineering practice, we also think it is important to consider how engineering practice may continue to evolve, and how we as researchers, educators, and instructors can transform the field of engineering to center diversity, equity, and justice.

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Chapter 3 "You Could Take 'Social' Out of Engineering and be Just Fine:" An Exploration of Engineering Students' Beliefs about the Social Aspects of Engineering Work[9]

3.1 Introduction

Engineering is an inherently social discipline. The social aspects of engineering work include the various ways that engineers, within the context of their professional roles, impact, interact with, and relate to both broader society and other individuals. For example, engineering work produces significant and long-lasting impacts on society, and engineers are responsible for understanding the potential societal implications of their solutions (Fila et al., 2014; Accreditation Board for Engineering and Technology, 2022; National Academy of Engineering, 2004; Niles et al., 2020). As another example, engineers may work closely with communities and stakeholders as part of their problem definition and solution development processes (Fila et al., 2014; Luck, 2018; Nieusma & Riley, 2010; Niles et al., 2020). Furthermore, communication and collaboration are core aspects of professional engineering practice. To achieve optimal engineering outcomes, engineers must be able to work effectively with diverse teammates and co-workers (Fila et al., 2014; Trevelyan, 2007, 2010; Passow & Passow, 2017).

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Engineering students engage with the social aspects of engineering work in several contexts, including internships and project-based design courses. However, previous studies have observed variations and gaps in the ways that engineering students conceptualize the social aspects of their work. For instance, some engineering students may consider stakeholder engagement to be a core aspect of engineering practice, while other engineering students may view this engagement to be largely unnecessary (Loweth et al., 2019, 2021; Zoltowski et al., 2012). Engineering students may also vary substantially in the degree to which they consider the broader societal contexts of their engineering problems (Atman et al., 2008). Furthermore, some engineering students may conceptualize engineering work as being purely technical and may thus struggle to apply "non-technical" knowledge and approaches when developing engineering solutions (Khosronejad et al., 2021; Niles et al., 2020). In part, these variations and knowledge gaps may emerge because strong, intentional education about the social aspects of engineering work is not often included within standard undergraduate engineering curricula (Niles et al., 2020; Schneider et al., 2008; Sienko et al., 2018).

Our preliminary study investigated junior- and senior-level engineering students' beliefs about the social aspects of engineering work based on their previous education and internship experiences. Students' beliefs about engineering work represent an important research topic because of how these beliefs may influence engineering practice and outcomes (Cech, 2013; Fila et al., 2014). Specifically, in the context of this study, the investigation of students' beliefs can deepen our understanding of how engineering students may think about and apply knowledge related to the societal contexts of their engineering work. The investigation of students' beliefs can also provide insight into the specific ways that engineering students may be perpetuating normative conceptions of engineering work as being separate from social concerns and/or unintentionally contributing to existing systems of inequality or exclusion within engineering environments. Studying students' beliefs in the context of their previous experiences further enables us to explore how students may acquire their beliefs about engineering work, and thus can inform pedagogy that supports engineering students in developing more inclusive views of engineering.

3.2 Background

3.2.1 Social aspects of engineering work: Engineering with, for, and as people

There are several ways to conceptualize the social aspects of engineering work. One useful framework, which forms the basis for our later analysis, is the "engineering *with*, *for*, and *as* people" framework described by Fila et al. (2014). This framework does not encompass all social aspects of engineering work: for instance, it does not discuss in depth the systems-level interactions between engineering work and the broader social, political, environmental, and/or economic contexts within which this work occurs. However, this framework does provide a clear summary of key ways that engineering is a social discipline in addition to a technical discipline.

Engineers work *with* people. Engineering *with* people involves collaborating with stakeholders and communities to produce successful and equitable engineering outcomes. In engineering domains such as product or service design, stakeholders represent valuable sources of information that can help engineers understand the goals of their engineering work and evaluate the feasibility of potential solutions (Dieter & Schmidt, 2013; Rosenthal & Capper, 2006). Case studies such as Luck (2018) and Østergaard et al. (2018) also show that, through participatory or co-creative techniques, engineers can leverage the unique knowledge of stakeholders in the development of innovative solutions. Stakeholder engagement skills thus represent important knowledge for engineers to develop, although this knowledge is not typically covered as part of standard engineering curricula (Schneider et al., 2008; Sienko et al., 2018).

Engineering *with* people also includes the teams and organizations within engineering working environments. Trevelyan (2007, 2010), in his studies of professional engineering practice, observed that engineers spend a significant portion of their working time communicating and coordinating with teammates and co-workers. Olson et al. (1992) and Bucciarelli (1994) have similarly observed that engineers spend substantial time during technical meetings clarifying ideas to teammates and coordinating their projects. Passow and Passow (2017), in their review of literature related to core engineering competencies, highlighted collaboration skills as a crucial component of technical competence. Anderson et al. (2010), based on their investigation of engineering practice at six engineering firms, further suggested that some professional engineers consider communication and coordination skills to be the most important skills that they leverage to complete their work.

Engineering work should also be *for* the benefit of people and society. For instance, the Accreditation Board for Engineering and Technology (ABET) (2022) states that engineering graduates must be able to "apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors." Professional societies such as the National Academy of Engineering (2004) and the National Society of Professional Engineers (2013) also emphasize service to society as a core mission of engineering. The phrase "engineering *for* people" thus captures the aspirations of the engineering profession, especially if engineers can successfully engineer *with* stakeholders and communities. However, as described by Nieusma and Riley

(2010), engineers who work *for* people but not effectively *with* people risk perpetuating existing social inequities.

Lastly, engineers work *as* people, meaning that their personal and social identities influence their engineering work. Previous studies have documented how various aspects of engineers' personal and social identities, including domain background (Bucciarelli, 1994; Chou, 2020), psychological characteristics and personality (Chou, 2020; Kunrath et al., 2020), race (Chou, 2020; Harrington et al., 2019; Johnson et al., 2011; McGee, 2020; Ogbonnaya-Ogburu et al., 2020), gender (Chou, 2020; Faulkner, 2009; Johnson et al., 2011), socioeconomic status (Chou, 2020; Harrington et al., 2019; Smith & Lucena, 2016), and ability status (Holmes, 2018; Seshadri & Reid, 2015), may affect the ways that engineers interact with other engineers or stakeholders and/or apply their knowledge to solve problems. Engineering *as* people also refers to how engineers' ideas about "legitimate" engineering work may influence their work processes. For instance, Cech (2013) has suggested that, due to a culture of "depoliticization" in engineering, engineers may view their personal, social, and cultural values as disconnected from their engineering work and thus may not consider the implications of their positionality when engineering *with* or *for* people.

3.2.2 Engineering students' beliefs related to the social aspects of engineering work

Previous studies have described several beliefs that engineering students may possess about engineering work and the role of social or societal considerations within this work. For example, Khosronejad et al. (2021) studied how engineering students approached a simulated design task related to air pollution mitigation. They found that participants rejected solution ideas involving policy initiatives or stakeholder education because these solutions did not align with participants' conceptions of engineering work as the creation of physical artifacts. Studies such as Cech (2014) and Bielefeldt and Canney (2016) have also reported that engineering students' feelings of social responsibility may decline over the course of their undergraduate engineering education. Cech (2014) attributed this decline to a "culture of disengagement" in engineering education, i.e., a widespread belief that public welfare considerations are tangential to engineering work. As a result, engineering students may not view potential societal impacts as important factors to consider in the development of engineering solutions, although Rulifson and Bielefeldt (2019) have shown that students' attitudes about social responsibility may also be positively influenced by community-engaged, co-curricular projects and/or courses on engineering ethics.

Other studies have explored the relationship between engineering students' beliefs about engineering work and their approaches to interacting with stakeholders. Niles et al. (2020) suggested that some engineering students may struggle with the stakeholder engagement aspects of engineering work because these practices seem to conflict with the technocentric focus of traditional engineering education. In addition, Zoltowski et al. (2012) described a continuum of potential engineering student perspectives related to stakeholder engagement ranging from "Technology-centered" (i.e., no stakeholder involvement in design projects) to "Empathic design" (i.e., deep stakeholder involvement and relationship building). Building on this work, Loweth et al. (2019, 2021) observed that engineering students' perspectives on stakeholder engagement seemed to influence the techniques that students used to engage stakeholders in their design projects, as well as the frequency of their engagements.

Studies have also explored beliefs that engineering students may possess related to working or interacting with other engineers. For instance, Meyers et al. (2012) surveyed engineering students about the factors that they believed were necessary to be considered an engineer. Participants in their study consistently selected “Being able to work with others by sharing ideas” and “Speaking/communicating using accurate technical terminology” as key descriptors of engineers. In contrast to these findings, Dunsmore et al. (2011) reported that their engineering student participants described teamwork as an obstacle to be overcome rather than as a fundamental characteristic of engineering practice. Meanwhile, Litchfield and Javernick-Will (2015), in their study of engineering students’ engineering identities, found that engineering students who saw themselves as outgoing and/or interested in engaging with others also described these qualities as being atypical of engineers. These studies collectively suggest that there are a variety of ways that engineering students may conceptualize their interactions with other engineers, and thus also likely a variety of ways that students may approach interactions with other engineers in practice.

3.3 Methods

3.3.1 Research questions

While previous studies have identified potential ways that engineering students may conceptualize the social aspects of engineering work, our study sought to understand students’ beliefs in greater depth and also identify specific ways that students’ beliefs may be informed by their education and work experiences. Our study was guided by the following research questions:

1. What ideas related to the technical and social aspects of engineering work do engineering students feel align most and align least with their education and internship experiences?
2. When interpreting their previous experiences, how do engineering students describe the social aspects of their engineering work?

3.3.2 Participants

Thirty junior- and senior-level engineering students were recruited to participate in our study. Participants were recruited through a study solicitation and screening survey that was sent to university listservs in the Mechanical Engineering, Industrial and Operations Engineering, and Electrical Engineering/Computer Science departments at a large Midwestern university. We recruited participants from multiple engineering departments so that we could explore a range of potential disciplinary experiences. The screening survey collected basic demographic and contact information, and we leveraged stratified sampling (based on race, gender, and major) to maintain diversity in the collection of students that we invited to participate in interviews. Eighteen out of 30 participants in our final participant sample reported identifying as White, seven participants reported identifying as Asian American, three participants reported identifying as Black, and two participants reported identifying as multiracial. Fifteen out of 30 participants reported identifying as men, 14 participants reported identifying as women, and one participant reported identifying as non-binary. Academic information for our participants is included in Table 3.1. We have aggregated our participant data to conceal the identities of our participants, some of whom might be highly identifiable within their disciplines due to low overall diversity.

Table 3.1 Aggregate academic information for participants

Category	*n*	%
Total	30	100
Class Standing		
Junior (3rd year)	9	30.0
Senior (4th year)	20	66.7
>4th year	1	3.3
*Major**		
Mechanical Engineering	11	36.7
Electrical Engineering	11	36.7
Industrial and Operations Engineering	6	20.0
Computer Science	3	10.0
Biomedical Engineering	1	3.3

*Two participants indicated more than one engineering major

3.3.3 Synthesizing technical and social aspects of engineering work

In preparing the interview protocol for our study, we generated eight statements that captured key ideas related to the technical and social aspects of engineering work (shown in Table 3.2). We synthesized these eight statements from descriptions of engineering work found in reports published by engineering organizations (e.g., the National Academy of Engineering (2004, 2005, 2015, 2018)) and universities with an engineering focus (e.g., the Massachusetts Institute of Technology (Graham, 2018)), as well as the academic literature (e.g. Passow and Passow (2017)). We conducted pilot interviews with engineering practitioners to verify that our eight statements aligned with practitioners' perspectives of engineering work.

Our eight statements encompassed multiple ways that engineering is both a technical and social discipline. Statements such as "Engineering is a technical discipline" and "Engineering is a social discipline" highlighted these aspects of engineering work explicitly. Other statements communicated ways that engineering is simultaneously technical and social. The statement "Engineering is a team discipline" reflected the idea that engineers frequently collaborate to complete technical tasks. The statements "Engineering is a global discipline" and "Engineering makes the world a better place" were grounded in the idea that engineers' technical design decisions have far-reaching impacts on society. The statement "Engineering is about synthesizing and integrating knowledge" related to how engineers utilize both social and technical information to inform their design decisions. The statements "Engineering is a creative discipline" and "Engineering is constantly evolving" reflected how engineers' technical processes are flexible, iterative, and adapting in response to societal changes.

Table 3.2 Statements about engineering work synthesized from literature

Statement about engineering work	Definition	References
Engineering is a technical discipline.	Engineers use math and science to solve problems.	(Accreditation Board for Engineering and Technology, 2022; American Society for Engineering Education, 2013, 2018; Duderstadt, 2008; Graham, 2018; Kamp, 2016; National Academy of Engineering, 2004, 2005, 2015, 2018; National Society of Professional Engineers, 2013; Passow & Passow, 2017; Sheppard et al., 2009)
Engineering is a social discipline.	Engineers solve problems that impact people. These interventions inevitably have intended and unintended impacts on societies.	(Accreditation Board for Engineering and Technology, 2022; Duderstadt, 2008; Graham, 2018; National Academy of Engineering, 2004, 2005, 2015; National Society of Professional Engineers, 2013; Sheppard et al., 2009)
Engineering is a global discipline.	The world is increasingly interconnected. Technology is developed by diverse teams and can have far-reaching impacts on diverse stakeholders.	(Accreditation Board for Engineering and Technology, 2022; National Academy of Engineering, 2004; National Society of Professional Engineers, 2013; National Academy of Engineering, 2005; Graham, 2018; Duderstadt, 2008; Kamp, 2016; Kirkpatrick et al., 2011)
Engineering is a team discipline.	No individual can possess all of the technical expertise required for the complexity of modern engineering problems, and some essential knowledge for engineering practice is unwritten/implicit and can only be accessed through collaboration.	(Accreditation Board for Engineering and Technology, 2022; American Society for Engineering Education, 2013, 2018; Duderstadt, 2008; Graham, 2018; Kamp, 2016; National Academy of Engineering, 2004, 2015, 2018; National Society of Professional Engineers, 2013; Passow & Passow, 2017)
Engineering is a creative discipline.	Engineers explore unstructured problems and identify multiple paths to solutions.	(Accreditation Board for Engineering and Technology, 2022; American Society for Engineering Education, 2013, 2018; Duderstadt, 2008; Kamp, 2016; National Academy of Engineering, 2004; Passow & Passow, 2017)
Engineering is constantly evolving.	Advances in knowledge are so rapid that even the fundamentals of engineering are no longer fixed. Engineers need to continue learning throughout their careers to keep up with changes in technologies and the contexts in which they are used.	(Accreditation Board for Engineering and Technology, 2022; American Society for Engineering Education, 2013, 2018; Duderstadt, 2008; Kamp, 2016; National Academy of Engineering, 2004, 2005; National Society of Professional Engineers, 2013)
Engineering is about synthesizing and integrating knowledge.	Engineers solve complex problems by synthesizing information and approaches from STEM and non-STEM disciplines.	(Accreditation Board for Engineering and Technology, 2022; American Society for Engineering Education, 2013, 2018; Duderstadt, 2008; Graham, 2018; Kamp, 2016; National Academy of Engineering, 2004, 2005, 2015, 2018; National Society of Professional Engineers, 2013; Passow & Passow, 2017; Sheppard et al., 2009)

Engineering makes the world a better place.	The goal of making the world better for all people through engineering is both historical and aspirational.	(Accreditation Board for Engineering and Technology, 2022; Duderstadt, 2008; Graham, 2018; National Academy of Engineering, 2004, 2005)

3.3.4 Data collection

We conducted and audio-recorded a single 60 to 75-minute interview with each study participant. The first 22 interviews were conducted in person, and the remaining eight interviews were conducted over a video-conferencing software such as Zoom. During interviews, we provided participants with the eight statements about engineering work shown in the left-hand column of Table 2. Since our goal was to understand participants' genuine conceptions of engineering work based on their own experiences, we intentionally did not provide definitions for each statement. Rather, we encouraged participants to interpret each statement in ways that made sense to them, and to discuss experiences that aligned with their personal interpretations.

Before providing our eight statements about engineering work to participants, we first clarified the goal of the exercise: participants would be asked to select two statements that aligned most with their previous engineering experiences. Our process for providing our eight statements to participants then differed slightly between in person and remote interviews. During in person interviews, we printed each statement on individual slips of paper. The interviewer read these slips aloud one-by-one before handing each slip to the interviewee. Participants were free to arrange the eight slips as desired while thinking through their responses. During remote interviews, the interviewer sent participants the full list of eight statements via the software's chat function, and then read out the statements one-by-one. We did not notice differences in how participants' thought through their responses between in person and remote interviews.

After providing our eight statements to participants, we asked participants to select two statements that aligned most with their previous engineering education or work experiences. Once participants made their selections, we then asked participants to describe a story from their experiences that aligned with one of their selected statements. As participants shared their stories, we asked follow-up questions to clarify how participants connected their stories to their first selected statements. We repeated this process for participants' second selected statements.

We transitioned to the second part of our interview by clarifying that we would be using the same eight statements for a new exercise. We then asked participants to select two statements that aligned less well with their previous experiences and to discuss their rationale. We asked participants to discuss their rationale (rather than provide an example experience) because in many cases participants chose statements that had not played a significant role in their education and work experiences. However, participants were encouraged to share an experience that did not align with their chosen statements if they were able. Similar to the first part of the interview, we asked follow-up questions to clarify how participants interpreted each selected statement and how they connected these statements to their experiences (or lack thereof). Participants were allowed to choose statements that they had previously discussed as aligning with their experiences, but only one participant discussed the same statement twice. Recordings of interviews with participants were transcribed, and these transcriptions were checked for accuracy by a member of the research team.

3.3.5 Data analysis

To answer our first research question, we recorded the statements about engineering work that each participant selected as aligning most and aligning least with their education and internship experiences.

To answer our second research question, we analyzed participants' interview responses to identify specific ways that participants described the social aspects of engineering work.

First, two researchers reviewed participants' justifications for the statements that they selected as aligning most and aligning least with their engineering experiences. During this review, the researchers identified representative quotes that captured the main ideas or experiences shared by each participant. The two researchers also recorded, for each quote, the statement about engineering work that had elicited the quote. After completing this initial review, the two researchers grouped together quotes that conveyed similar experiences and/or ideas about engineering work and defined the central idea communicated by each group of quotes. An example of this grouping process is shown in Table 3.3. Building upon work by Godfrey and Parker (2010) and Schein (2016), we titled these central ideas collectively as "beliefs about engineering work." The two researchers then reviewed participants' interview responses again to identify additional participant quotes that had been missed during the initial round of review and that aligned with one of the identified beliefs. After completing this second review, the two researchers discussed discrepancies in their understandings of each identified belief, iterated on their definitions of these beliefs, and reached complete negotiated agreement as to the prevalence of each belief across participants' responses.

Our analysis process identified a diversity of beliefs about engineering work across participants. Beliefs about the social aspects of engineering work, particularly engineering *with*, *for*, and *as* people as defined by Fila et al. (2014), are reported in our findings. Most of these beliefs related to engineering *with* and/or *for* people. Participants discussed few beliefs that were directly related to engineering *as* people in reaction to our eight statements.

Table 3.3 Example of coding approach

Quotes from participants	Belief about engineering work
"*You'll get a lot farther if there's a group versus just one person trying to figure it out by themselves… Different people bring different things that can build on each other and make it into something good.*" (Participant 25) "*When we were doing data collection, data analysis, it was helpful to have multiple people for multiple ideas. Some people in the group noticed one thing that was significant in the data and another person would find something else in terms of patterns and discrepancies*." (Participant 19)	Engineering teams comprising diverse perspectives are more likely to develop successful engineering solutions than single engineers working alone

3.4 Findings

3.4.1 Statements about engineering work that aligned most and least with engineering students' education and internship experiences (answering RQ1)

Table 3.4 provides a summary of participants' choices for statements about engineering work that aligned most and aligned least with their experiences.

Table 3.4 Summary of participant choices for statements about engineering work that aligned most and aligned least with their education and internship experiences

Statement about engineering work	Align Most	Align Least
Engineering is a team discipline	17	1
Engineering is about synthesizing and integrating knowledge	15	5
Engineering is constantly evolving	7	10
Engineering is a technical discipline	5	2
Engineering makes the world a better place	5	9
Engineering is a creative discipline	4	10
Engineering is a social discipline	4	15
Engineering is a global discipline	3	8

Two statements were selected by at least half of our participants as aligning most with their education and internship experiences in engineering: "Engineering is a team discipline" (17/30 participants) and "Engineering is about synthesizing and integrating knowledge" (15/30 participants). After these two statements, the next most frequently selected statement was "Engineering is constantly evolving" (7/30 participants). The remaining five statements were each selected by five or fewer participants as aligning most with their engineering experiences.

The most common statement selected by participants as aligning less well with their engineering experiences was "Engineering is a social discipline," selected by 15 out of 30 participants. Other statements that were selected by at least a quarter of participants as aligning less well with their experiences included "Engineering is constantly evolving" (10/30 participants), "Engineering is a creative discipline" (10/30 participants), "Engineering makes the world a better place" (9/30 participants) and "Engineering is a global discipline" (8/30 participants). The remaining three statements were each selected by five or fewer participants as aligning less well with their engineering experiences.

3.4.2 Engineering students' beliefs about the social aspects of engineering work (answering RQ2)

Participants described a variety of beliefs about engineering work when discussing their selected statements. In this section, we report beliefs related to social aspects of engineering work that recurred across participants.

Participants discussed several beliefs related to working *with other engineers*, particularly in the context of statements such as "Engineering is a team discipline," "Engineering is about synthesizing and integrating knowledge," and "Engineering is a social discipline." These beliefs included: 1) collaboration with other engineers is an important part of successful engineering work, 2) effective communication is an important part of successful engineering work, and 3) personal friendships with teammates are not important for effective collaboration.

Fifteen out of the 17 participants (nine men, six women) who selected “Engineering is a team discipline” as aligning most with their experiences did so because they felt that collaborating with other engineers enabled them to achieve more successful engineering outcomes. In the words of one such participant:

“*I've found that if I don't work with others I won't be as successful. Even in classes that aren't project focused or team-oriented, I've found that just working with other people and clarifying things you maybe don't understand in lecture and just studying together [can be] overall beneficial. People can usually accomplish more as a group than individually… If I had to do everything myself, it would not get done.*” (Participant 22)

Ten of these 15 participants (five men, five women) additionally emphasized the value of including diverse perspectives within their engineering collaborations. For example:

“*People with different backgrounds can talk about and critique different things. That's always really useful, especially in a creative setting for brainstorming as well as design reviews, seeing if you have any glaring issues that maybe made sense to you but to someone else just doesn't work.*” (Participant 2)

As illustrated by this quote, several participants perceived clear benefits in including diverse engineering perspectives in their engineering work, particularly because engineers with different backgrounds might identify different types of potential problems. Other participants similarly emphasized that engineers with diverse perspectives might identify different types of solutions during ideation activities and/or contribute different and complementary types of knowledge during solution development.

Participants also discussed the role of communication in working with engineers. For instance, when discussing how "Engineering is a team discipline" aligned with their experiences, six participants (four men, two women) stressed that effective communication with teammates was a necessary part of engineering work:

"[Engineering] is about communication, and not just being technically skilled. Being able to explain to your other teammates what you're doing and also what you need from them to make your project integrate with everyone else… you have to speak up and be clear about where you're at so that everyone's on the same page." (Participant 24)

As described by this participant, engineers need to communicate effectively as part of their work to ensure that team members possess equivalent understandings of the project and can properly integrate their work outcomes. Five other participants (two men, three women) similarly stressed the importance of effective communication with teammates during discussions of "engineering is about synthesizing and integrating knowledge" and "engineering is a social discipline."

Five participants (one man, four women), during discussions of "engineering is about synthesizing and integrating knowledge" and "engineering is a social discipline," further emphasized the importance of effective communication for gathering needed information. As explained by one participant:

"*I've been repeatedly told engineering is about how you talk to people, what knowledge you get out of them, and then how you put that knowledge together, more than it is about being a genius or being super creative… A lot of learning in engineering is, how do you say it? Oratory? It's passed down. It's not documentation. Of course, you're encouraged to have documentation, but that's not how the real world usually works… It's really important that you talk to people and synthesize everything you learn from them.*" (Participant 5)

In other words, relevant engineering knowledge is often distributed across individuals rather than available through a central resource or database. As such, engineers should be able to gather needed information from multiple individuals and synthesize this information as part of their engineering work.

Participants mainly interpreted the statement "Engineering is a social discipline" in terms of interpersonal interactions between engineers. Seven out of 15 participants (two men, four women, one non-binary) who said that this statement aligned less well with their experiences emphasized that personal friendships were not a prerequisite for collaborating effectively with other engineers. As described by one participant:

"*I feel like engineering classes aren't made to be social and interactive at all. They are meant to be collaborative, which is why I do believe that engineering is a team discipline, but not necessarily social in the way where I see interpersonal relationships as defining the work that you do…And while I believe teams do better when there's common ground and social interaction… I don't think it is a prerequisite in order to do your work… I think collaborating and being able to communicate or being able to read a room is really important, but I don't think* *social is, like your ability to 'bond' or 'get along' with your teammates, because there's very few people I talk to in my classes.*" (Participant 15)

One of the ways that this participant distinguished between "social" and "collaborative" activities in engineering was by referencing their curricular environment: most of their engineering classes were meant to be collaborative (i.e., encouraging teamwork), but not necessarily "social" (i.e., encouraging friendships between students). Participants discussed other ways that their engineering education and work environments seemed to discourage "social" behavior as well. For instance, four participants (three men, one woman) described team project experiences that involved limited interaction with teammates beyond what was necessary to complete their projects. Three participants (two women, one non-binary) described research or internship experiences that involved working alone at a desk with minimal interaction with other engineers. Furthermore, two participants (one man, one woman) discussed how the competitive nature of engineering classes tended to discourage social behavior. These various experiences provided additional reasons that participants in our study felt that the statement "Engineering is a social discipline" did not align well with their experiences.

In addition to beliefs about working with other engineers, some participants also discussed beliefs related to the social impacts of engineering work. Discussions of social impacts most consistently occurred in the context of the statement "Engineering makes the world a better place." For example, seven participants who selected the statement "Engineering makes the world a better place" discussed how the goal of engineering work is to improve society, such as in the following quote:

"*Engineering has improved a lot of aspects of life over the past 100 years, whether that's transportation, healthcare… Using technology to find solutions is definitely something that I see that engineering does and that's why I really enjoyed my time here [in college], working on projects that I feel can have that type of impact, and that's what I'm looking forward to doing in the future as well.*" (Participant 14)

This participant felt that the outcomes of engineering work have improved many aspects of society, which is why this participant felt that engineering did indeed make the world a better place. Including this participant, three of the seven participants (all men) who discussed improving society through engineering felt that "Engineering makes the world a better place" aligned with their experiences. The other four participants (one man, two women, one non-binary) felt that "Engineering makes the world a better place" did *not* align well with their experiences; these four participants described improving society as an aspiration rather than as a reality of engineering work.

Other beliefs related to the social impacts of engineering work that recurred in our data were: 1) engineers should consider the broader societal implications of their engineering work and 2) engineers should consider the needs of their stakeholders. For instance, the following quote from a student who felt that "engineering is a social discipline" did not align well with their experiences relates to the consideration of broader societal implications:

"*It is important to realize how the stuff that you do could affect the community that you live in or the people that you are actually doing it for. I feel like it might be easy to forget while you're in engineering that what we're trying to do is generate power for the people and for your own* *families. I feel it's important to take a step back instead of just focusing on specific project or specific technicalities that you're working on.*" (Participant 25)

However, participant quotes related to the consideration of broader societal implications and/or stakeholders in engineering work were scattered across statements rather than occurring in response to any particular statement. In other words, although several participants seemed to believe that engineers should consider broader societal implications and stakeholders, none of our eight statements consistently elicited discussions from participants related to these beliefs.

3.4.3 Case example of a single engineering student's descriptions of working with other engineers (answering RQ2)

In total, 28 out of 30 participants discussed beliefs related to working with other engineers, particularly in the context of "Engineering is a team discipline," "Engineering is about synthesizing and integrating knowledge," and "Engineering is a social discipline." This section of our findings delves into the specific experiences and beliefs of one of those participants (hereafter referred to by the pseudonym of Susan), who reported identifying as a White woman. This participant was selected as a case example because she was one of three participants who selected both "Engineering is a team discipline" and "Engineering is about synthesizing and integrating knowledge" as aligning most with their engineering experiences, as well as "Engineering is a social discipline" as aligning less well with their experiences. While this specific case does not reflect the perspectives of all students in this study, it does provide important additional context that illustrates in greater depth how some of our participants seemed to conceptualize the differences between "social bonding" and "collaboration."

“Engineering is about synthesizing and integrating knowledge” was the first statement selected by Susan as aligning most with her engineering experiences. When discussing this statement, Susan described an internship experience where her company tasked interns with developing an engineering solution to a business problem as part of an internal competition. Susan felt that this experience demonstrated the statement “Engineering is about synthesizing and integrating knowledge” because she was required to gather relevant information from a variety of sources and synthesize this information to develop an effective product. As she described:

“*A lot of what we did in the group was pull together all of the different experiences we'd had in industry and in classrooms, and in our extracurriculars, and in our own readings in free time. Then, we combined [these experiences] with knowledge and information that we gained from user interviews and the business managers, and our problem statements and everything… and analyzed [this information] to really build something that had the potential to be useful… That whole process of taking all of your past knowledge and all of the situational knowledge that you can gather and coming up with a new idea to solve a problem is something that I've seen repeated through all of my different engineering experiences.*”

As part of this experience, Susan identified two different types of individuals from whom engineers may gather information related to their engineering work: users and business managers. By specifying “interviews,” Susan also indicated that engineers gain information about users through direct interaction. This quote thus relates to other participants’ discussions about the need to communicate effectively with other individuals as part of engineering work, while additionally highlighting the importance of communication with non-engineers as well.

"Engineering is a team discipline" was the second statement selected by Susan as aligning most with her engineering experiences. Susan felt that this statement was exemplified by her experiences volunteering annually as part of a high school STEM competition. As described by Susan, the role of the volunteers was to support competitors in working through technical difficulties that they encountered while setting up their projects. Each of the volunteers brought unique skill sets (e.g., some volunteers were better at programming, while others were better at wiring or pneumatics) and volunteers coordinated closely to provide an optimal level of technical support across all teams participating in the competition. This coordination aspect of her volunteering experience was particularly salient for Susan:

"*I picked that story because it was important to me that it's not always best to do it all yourself. It would have taken me a lot longer, and I was extremely grateful for everyone on that volunteer team, and all the people that we were able to pull in that were happy to help because we were able to get [the student teams] up and running so much faster… On my own, I wouldn't have been nearly as effective and probably would have been much more flustered and angry, and not communicated as well. With the support of a whole team, we were able to handle the situation.*"

Similar to other participants, Susan highlighted collaboration as a core aspect of effective engineering work. For instance, by working together, the volunteer team was able to leverage their respective skill sets to get student teams up and running quickly. By comparison, Susan noted that trying to support student teams on her own would have been ineffective and likely would have made her feel frustrated and angry.

Susan selected “Engineering is a social discipline” as aligning less well with her engineering experiences. When justifying her selection, Susan described a curricular experience where she worked with three different teams over a single semester. Comparing across these three team experiences, Susan found that:

“*Among those three groups, it was interesting to watch how effective the team was as compared to how close the people on that team were. It actually turned out... these things carry across what I've seen in other classes as well, but the effectiveness of the team, you didn't actually have to know the other people very well, you really only needed to know their skills and be able to communicate with them effectively. You didn't need to know what they were doing in their personal lives and you didn't need to be their best friend...*”

Susan elaborated on this point by comparing the experiences of two teams in greater depth. One team, which Susan identified as her favorite, was described by Susan as “not close and very effective.” She described her experience working on this team as follows:

“*We'd all split up into our little groups. We found it effective in that group to only focus on the tasks at hand. We communicated well and got along and it was a good time, but we didn't walk out of there with new best friends or anything like that. Instead of spending that time building social bonds, we were able to spend that time building almost like professional bonds or working* *bonds that we found were effective in solving problems, staying calm on competition day, and knowing who had what skills.*"

Susan enjoyed her experience on this team because her team members were focused on their group project and leveraged their respective skill sets effectively to develop a successful solution. Susan juxtaposed this experience with another team experience that she described as "close, but not effective:"

"*One of the people on the final project team, they just liked to know what you were up to and how your weekend was and, 'Oh, it would be really cool if ...' like kind of bringing passions into our project. It's good to have passion for a project, but then it was really easy to get distracted on, 'Ah, it would be so cool if we painted it red or if we could grow 95 types of seeds in it,' or, 'These are all the things I would do,' and like, 'This is how we could draw it out because it would be fun,' and we would get really distracted. There's a whole bunch of fun things to talk about, but it would sidetrack us from the actual project and then we'd forget what we were doing and forget who was doing what. We'd kind of lose focus almost, and I walked out of there with great friends but not a great project. It was kind of a trade-off, like, 'Now I can talk to you all day about our project that didn't work.' There have been a couple teams where I walk out with both friends and a project, but most of the time if I have friends I will only have an okay project.*"

Susan felt that this project team was less effective because of their "social" interactions. While the experience was enjoyable from a personal standpoint, the team frequently became side-tracked by personal discussions and ultimately failed to develop a working product.

Thinking across her previous team experiences in general, Susan saw little connection between developing close relationships with teammates and achieving successful engineering outcomes. As she explained:

"*I have had teams that were composed of my friends and were not effective at all. I've had teams that were composed of friends that were effective, but I haven't seen any correlations between being close with the people around you and spending a lot of time on social activities and getting to know one another, and the actual outcome of your project. While there are aspects of engineering that are, not to say that being social isn't important to engineering, but I think you can get away without a lot of it. Out of the list of [statements] here, it's the one that I think you could, you could take 'social' out of engineering and be just fine, but I think the rest of the things on your list here you really do need in engineering. Because, all you need to be able to do is communicate effectively, but you don't need to know how everybody's kids are doing or if they went to the Bahamas. It's not as important to form those social bonds to create a good product as it is to understand your team's skills and how they like to communicate.*"

As such, Susan felt that the ability to communicate effectively with team members was a much greater predictor of engineering team success than personal feelings of closeness between team members. Susan identified several topics of discussion, such as family or vacations, that might be nice to know at a personal level but were ultimately irrelevant to engineering work. In that sense, Susan felt that the statement "Engineering is a social discipline," as she interpreted it, was negotiable as a descriptor of effective engineer work, especially compared to the other statements provided during her interview.

3.5 Discussion

3.5.1 Engineering students' conceptions of "social" in engineering contexts

As described in our background and methods, there are many ways that engineering qualifies as a social discipline. Engineering work broadly impacts society at both local and global levels, and these impacts affect both present and future generations. Engineers also collaborate with users and stakeholders, particularly in co-design contexts, and often work with other engineers to complete engineering tasks.

We provided participants with eight statements that reflected various technical and social aspects of engineering work. Our open-ended exploration of participants' engineering experiences using these eight statements revealed participants' implicit conceptions of what "social" does and does not refer to in the context of engineering. Our participants emphasized the role of teamwork in their previous engineering experiences and highlighted the importance of employing effective strategies for collaboration and communication. Ten participants also discussed how collaborations in engineering benefitted from the inclusion of diverse perspectives. This latter finding in particular aligns with observations made by Benedict et al. (2018), who found that first-year engineering students similarly recognized the advantages of including diverse ways of thinking within engineering teams.

However, as explored in greater depth with the case of Susan, several participants differentiated collaboration and communication from other activities that they considered to be less important for engineering work, such as getting to know teammates personally or building friendships with peers. Participants often described these latter activities as being more "social" in nature. Based on this interpretation of "social," 15 out of 30 participants felt that the statement "Engineering is a social discipline" did not align well with their experiences.

Participants' discussions of the social aspects of engineering work mainly related to interactions between engineers. Few participants discussed beliefs related to engineering with stakeholders. Discussions of the social impacts of engineering work were also relatively limited. Participants indicated that engineering work should positively impact society when discussing the statement "Engineering makes the world a better place," but this statement was chosen infrequently overall (5/30 participants for "align," 9/30 participants for "not align"). Participants also generally touched on the importance of considering societal implications or stakeholder needs as part of their engineering work, but these discussions were not connected to any particular statement.

There are a few possible reasons why our participants may have interpreted the statement "Engineering is a social discipline" mainly in terms of interpersonal interactions rather than the social impacts of engineering work. For instance, participants may have felt that the social impacts of engineering work were sufficiently captured by the statement "Engineering makes the world a better place." Another explanation is that participants might not have readily associated "social" with "social impacts" due to limited engagement with the social impacts of engineering work in their previous education and internship experiences. Participants may also have interpreted "social" as referring to interpersonal interactions due to common uses of the word "social" in modern culture (e.g., "social" media). Furthermore, several common stereotypes (e.g., as compiled by Riley (2008)) portray engineers as "antisocial" and/or socially awkward. These stereotypes of "antisocial" engineers may be very salient for engineering students; Litchfield and Javernick-Will (2015), for instance, described engineering students spontaneously mentioning and subsequently rejecting these stereotypes when discussing their engineering identities. Thus, stereotypes of “antisocial” engineers may have influenced how participants in our study interpreted the word “social” as well.

There are also several potential explanations for why our participants seemed to view collaborating with teammates as a separate and distinct activity from befriending teammates (i.e., “social bonding”). The first potential explanation relates to how collaborative activities seemed to be framed in participants’ coursework. Participants indicated that collaboration was often a core, explicit part of their engineering assignments. However, based on participants’ accounts, it seems that engineering courses did not typically discuss the ways that informal, interpersonal interactions might affect engineering collaborations. As a result of these curricular experiences, our participants may have possessed relatively narrow understandings of collaboration as a core aspect of engineering work. In other words, our participants seemed to recognize the value of collaboration for completing technical tasks but may have possessed limited conceptions of how interpersonal dynamics might impact collaboration outcomes.

Our participants may also have differentiated collaboration from social bonding because they felt that “work” and “life” represented separate spheres of activity. For instance, several of our participants indicated that building friendships with peers was generally important; they just felt that socializing should occur in separate settings or at separate times from technical engineering work. Additionally, participants seemed to recognize the value of building professional relationships with teammates that were grounded in shared work experiences. Participants did not feel that personal bonding was necessary for such professional relationships to be successful. As described by Susan: “It's not as important to form those social bonds to create a good product as it is to understand your team's skills and how they like to communicate.”

A third potential explanation is that our participants' differentiation of collaboration from social bonding may reflect a technical/social dualism in students' beliefs about working with other engineers. This explanation stems from the consistent emphasis that participants placed on the technical goals and contexts of their collaborations. As defined by Faulkner (2000) based on a review of prior literature, the technical/social dualism refers to the tendency of engineers to prioritize technical knowledge as core to engineering work while devaluing interpersonal competencies. For example, engineers may view their ability to use tools as more important to their engineering work than their ability to manage other engineers. In the context of engineering educational environments, Tonso (2006b) has also described how "social" traits such as friendliness and an awareness of teammates' personal interests may go unrecognized and uncelebrated compared to technical expertise. Faulkner (2000, 2009) and Tonso (2006b) have both noted that the technical/social dualism (i.e., valuing technical knowledge over interpersonal skills) frequently encompasses stereotyped gender norms (technical = masculine, social = feminine) and thus reinforces the centrality of maleness in engineering at the exclusion of women.

Regardless of the explanation, there are several reasons to be concerned that engineering students may perceive social bonding as separate from, and less important than, the technical aspects of collaboration. For example, due to this differentiation, engineering students may downplay or otherwise fail to recognize the contributions of teammates that they perceive as acting in more "social" (i.e., interpersonal, people-oriented) ways. This dynamic may contribute to the exclusion of women engineering students in particular, since work by Tonso (2006b) indicates that women students, regardless of their technical expertise, may be perceived by teammates as inhabiting more "social" team roles. Findings from Meadows and Sekaquaptewa

(2013) further suggest that women engineering students may even perceive their relegation to more “social” (i.e., people-oriented) team roles as voluntary, despite viewing such roles as less desirable than the more technical roles inhabited by male teammates. Cross and Paretti (2020), in their study of African American male engineering students’ experiences in teams, also found that informal social interactions played an important role in enabling their participants to feel comfortable in mixed race teams. The devaluing of social interactions, particularly by White engineering students, could thus have adverse effects on minoritized students’ feelings of belonging in engineering.

Furthermore, it was not always clear how participants defined “building friendships” and “social bonding.” For instance, Susan described social bonding as the sharing of personal information that was irrelevant to engineering activities. However, several participants emphasized the value of including diverse perspectives within their collaborations, suggesting that there could be some types of personal information that may be relevant to engineering and thus okay to share. The ways that engineering students distinguish between relevant and irrelevant personal information has important implications for inclusion within engineering spaces. As one example, Smith and Lucena (2016) found that low income, first generation engineering students possessed unique and important engineering competencies that they had developed through their personal experiences. It is unclear whether such students would be able to leverage, or would even mention, their experiential knowledge in cases where their peers considered the discussion of personal experiences to be outside the realm of legitimate engineering work.

Lastly, drawing clear distinctions between “social bonding” and collaboration may ultimately be counterproductive for professional engineering practice. Professional engineers often switch between a variety of technical and social roles throughout a typical workday (Faulkner, 2000; Hatmaker, 2012; Trevelyan, 2007, 2010). Hatmaker (2012), in particular, in her study of professional engineering roles, demonstrated that building personal relationships with co-workers and clients is an important part of professional engineering work. Engineering students who believe that bonding with their collaborators is unnecessary may thus be losing opportunities to develop necessary interpersonal competencies prior to entering the workforce. Furthermore, these students may also consequently struggle to understand the value of other engineering practices that seem "non-technical" in nature, such as stakeholder engagement, but that are integral to effective engineering work.

3.5.2 Limitations

The open-ended nature of our interview protocol enabled participants to discuss their engineering experiences and their beliefs about engineering work in depth. However, our interview questions did not explicitly ask participants to share their beliefs; rather, this information emerged naturally as participants described and interpreted their prior experiences. As such, participants may have possessed beliefs about engineering work that were relevant to this study but that did not emerge during interviews.

Participants also did not consistently interpret our eight statements about engineering work (Table 2) as intended. In particular, we originally meant for "Engineering is a social discipline" to capture, at least in part, the broader societal implications of engineering work. However, most participants interpreted this statement in terms of interpersonal interactions instead. Since we did not define our eight statements for participants, it is unclear if participants' interpretations of "Engineering is a social discipline" reflected participants' narrow understanding of the social aspects of engineering work or rather a lack of clarity in the statement itself.

A third limitation was the relative lack of racial diversity across our participant sample, with 60% of participants reporting White as their racial identity. Engineering students with other racial identities would likely discuss different beliefs about engineering work.

Furthermore, our research team was composed of three White women and two White men who possessed a range of experience levels from undergraduate engineering student to tenured faculty member. Shared identities between our research team and many of our participants facilitated our data collection and data analysis processes. However, we also recognize that there are several potential ways to interpret our data, and the points that we highlight in our discussion section are in part informed by our personal perspectives. A different set of researchers (and particularly researchers of color) might draw different insights from our data and/or frame their findings in a different way. It is also possible that a more racially diverse research team would have elicited different interview responses from the same sample of participants.

Lastly, it is possible that our sample of participants may have been particularly social or outgoing compared to their peers. Our study solicited participants through emails to department listservs, meaning that our participants were all volunteers. It is unclear whether less outgoing engineering students would be interested in volunteering as study participants. This potential over-weighting towards outgoing engineering students could explain why many of our participants chose "Engineering is a team discipline" as aligning with their engineering experiences.

3.5.3 Implications

Engineering instructors can use our findings to support engineering students in developing more holistic views of engineering as a social discipline. For instance, relatively few participants discussed the societal impacts of engineering work in depth. In part, this finding may have emerged due to a gap in students' understandings about the social aspects of engineering work. However, this finding may also reflect a gap in students' engineering education, since few participants described curricular or work experiences where the societal impacts of engineering work were evident. As such, engineering instructors might support students in developing deeper conceptions of engineering as a social discipline by centering the societal impacts of engineering work in their curricula. For instance, instructors might reframe homework problems to reflect the societal contexts of engineering work (e.g., as described in Leydens & Lucena, 2018). Depending on the course topic, instructors might also introduce content related to social context assessments. However, given the traditional technocentric focus of engineering educational culture, instructors should be prepared to navigate potential pushback from students that may occur in response to centering the societal impacts of engineering work in their curricula.

Engineering instructors might also use our findings to restructure team- or group-based assignments for their courses. Recommended practices for team formation have been described extensively by previous studies. For example, instructors should sort students into heterogeneous teams that include diverse perspectives (Curşeu & Pluut, 2013). Instructors should also try to balance the gender or racial composition of their teams as much as possible (Cross & Paretti, 2020; Meadows & Sekaquaptewa, 2013; Tonso, 2006a). However, our findings suggest that even if engineering instructors follow recommended practices for team formation, some engineering students (particularly White students, given the demographics of our participant sample) might still inadvertently adopt exclusionary behaviors within their teams due to personal beliefs about what "productive" collaboration does and does not entail.

Engineering instructors may be unaware that exclusionary team interactions are occurring since instructors are often responsible for monitoring many teams simultaneously and the majority of team work for courses such as capstone may occur "outside" of the classroom. However, since the beliefs described by our participants were strongly influenced by their curricular and work experiences, our findings point to ways that instructors might adjust curricular environments to reduce the likelihood of exclusionary team behaviors. For instance, instructors might reduce the amount of work required to complete their projects so that students feel less inclined to adopt a "divide and conquer" approach that minimizes interactions between team members. Instructors might also introduce content into their curricula that highlights the interpersonal dimensions of professional engineering practice and supports students in developing skills for effective and inclusive collaboration. Instructors might further reduce the likelihood of exclusionary team behaviors by implementing inclusive teaching practices, such as openly acknowledging and valuing the contributions of diverse students and fostering a sense of community in their courses.

Based on our findings, instructors might also conclude that they should incorporate "social" criteria for their team projects that incentivize teammates to get to know one another personally. On the surface, this approach seems like it might address the potential distinctions that (particularly White) engineering students may draw between the "technical" and "social" aspects of collaboration. However, we would caution *against* such an approach, at least without significant forethought, because it potentially ignores the specific barriers that minoritized students often encounter in engineering educational contexts and might even create additional barriers to participation for students who may struggle to engage with their peers due to their identities. Ultimately, as suggested by Faulkner (2000, 2009), Tonso (2006b), Riley (2008), and others, the tendency of some engineers to downplay the interpersonal aspects of their engineering work is as much a reflection of engineering culture as it is an individual characteristic. Long-term, equitable solutions thus require cultural change beyond simply individual change.

3.6 Conclusion

Our study explored the beliefs that junior- and senior-level engineering students possessed about the social aspects of engineering work based on their previous education and work experiences. We provided participants with eight statements related to the technical and social aspects of engineering work and asked them to select two statements that aligned with their experiences and two statements that did not align well. Most (17 out of 30) participants selected "Engineering is a team discipline" as a statement that aligned closely with their previous experiences and, during discussions of this statement, highlighted the importance of communication and collaboration for effective engineering work. However, 15 out of 30 participants selected "Engineering is a social discipline" as a statement that aligned less well with their experiences; participants often justified their choice by describing how "social" activities, such as befriending teammates, are separate from and unnecessary for effective collaboration. Our findings thus seem to indicate a potential technical/social dualism in how engineering students may perceive their collaborations with other engineers. Our findings also suggest that some engineering students may hold narrow conceptions of the social aspects of engineering work, since discussions related to collaborating with users or communities and/or evaluating the social impacts of engineering work were relatively limited across our participant sample. By highlighting specific gaps in the ways that engineering students may conceptualize the social aspects of engineering work based on their previous experiences, our findings can support engineering instructors in adjusting their engineering curricula to promote more holistic and inclusive views of engineering.

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Chapter 4 Assessing Needs in a Cross-Cultural Design Project: Student Perspectives and Challenges[10]

4.1 Introduction

Identifying and evaluating stakeholder "needs" – the measurable gaps between stakeholders' present conditions and a hypothetical set of preferable conditions (Witkin & Altschuld, 1995; Watkins et al., 2012; Zenios et al., 2010; Royse et al., 2009; Sleezer et al., 2014; Darcy & Hofmann, 2003) – is an important aspect of design projects (IDEO, 2015; Bryden & Johnson, 2011; Wood & Mattson, 2014; Lucena et al., 2010). Previous studies have shown that project failures, especially in cross-cultural design contexts, can often be traced back to poor understanding of stakeholder needs (Lucena et al., 2010; Nieusma & Riley, 2010; Wood & Mattson, 2016; Mazzurco & Jesiek, 2014; Mink et al., 2018). Challenges in identifying and evaluating stakeholder needs are heightened in cross-cultural contexts due to significant cultural differences between designers and stakeholders (Wood & Mattson, 2014; Lucena et al., 2010; Nieusma & Riley, 2010; Wood & Mattson, 2016). As such, designers who will be working in cross-cultural contexts need to develop competencies for stakeholder and community engagement and combine these competencies with previous technical knowledge as part of a rigorous process for needs identification and evaluation (Leydens & Lucena, 2018; Nieusma & Riley, 2010; Sienko et al., 2018; Wood & Mattson, 2016).

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Needs assessments – rigorous processes for needs identification and evaluation – are described in disciplines as diverse as general organizational planning (Witkin & Altschuld, 1995), international development (Watkins et al., 2012), medical device design (Zenios et al., 2010), and social work (Royse et al., 2009). While specific methodology changes slightly with context, all of these fields emphasize that needs assessments are open-ended, reflexive, and iterative so that needs assessment teams can fully explore stakeholder perspectives on needs and recognize how their own individual subjectivity influences their perceptions of these needs (Darcy & Hofmann, 2003; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010). The goal of conducting needs assessments is to help ensure that any implemented solution addresses real stakeholder needs.

Undergraduate engineering students are increasingly participating in cross-cultural, community-oriented design projects involving the identification and evaluation of community needs – in other words, projects where needs assessments should be conducted. Many of these projects are initiated and led by the students themselves (e.g., Harshfield et al., 2009; de Chastonay et al., 2012; Magoon et al., 2010; McDaniel et al., 2011). However, engineering students often have limited prior needs assessment skills because pedagogy related to these skills is not part of standard undergraduate engineering curricula (Sienko et al., 2018; Leydens & Lucena, 2014; Vanasupa et al., 2006; Schneider et al., 2008). For example, few engineering programs offer instruction on how to engage with stakeholders within communities, which is a central activity in needs assessments (Baillie et al., 2010; Leydens & Lucena, 2014; Schneider et al., 2008), and the literature documents that students often struggle with community engagement aspects of their cross-cultural projects (Aslam et al., 2014; Harshfield et al., 2009; Mazzurco & Jesiek, 2014; Wood & Mattson, 2016). While some programs have developed student training opportunities for community engagement (e.g., Leydens & Lucena, 2018; *Socially Engaged Design Academy*, n.d.), detailed accounts of engineering students employing these engagement skills in practice are rare. Thus, we studied an undergraduate student team engaged in a cross-cultural design project to understand what these engineering students knew about needs assessments, how they conducted a needs assessment as part of a cross-cultural design project, and their learning gains from their needs assessment experience.

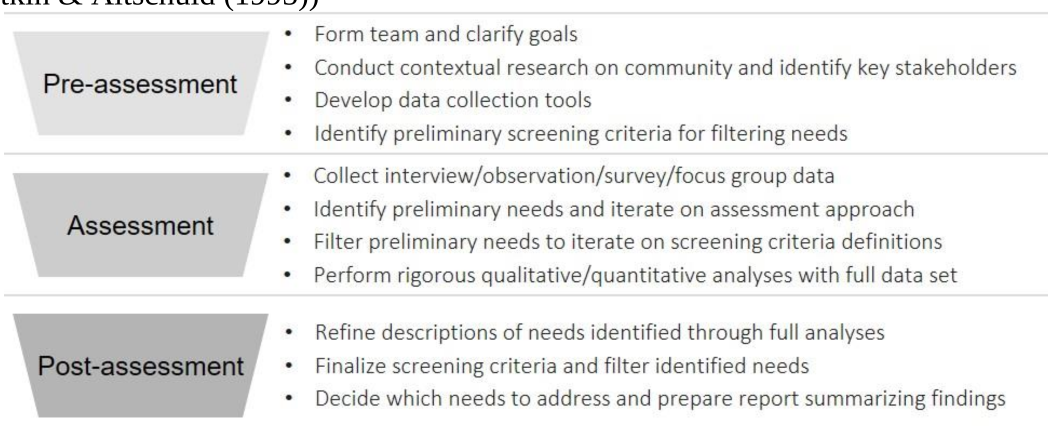
4.2 Background

4.2.1 Needs assessment as a rigorous needs identification and evaluation process

A "needs assessment" is "a systematic set of procedures undertaken for the purpose of setting priorities and making decisions about program or organizational improvement and allocation of resources. The priorities are based on identified needs (Witkin & Altschuld, 1995, p. 4)." Methodologies resembling needs assessments have been employed in cross-cultural design projects in the past (e.g., Bryden & Johnson, 2011; Lucena et al., 2010; Wood & Mattson, 2014); however, descriptions of these methodologies have focused mainly on practices for needs identification rather than comprehensive assessment of and decision-making about needs. Needs assessments represent a process that designers in cross-cultural contexts could use not only to identify stakeholder needs but also to evaluate these needs and decide which needs the design team could most realistically address (Sienko et al., 2018).

Needs assessments involve three main phases of activity: pre-assessment, assessment, and post-assessment (Watkins et al., 2012; Witkin & Altschuld, 1995) (summarized in Figure 4.1). During the pre-assessment phase, a diverse team should be assembled. This team should work together to clarify goals for the needs assessment, conduct contextual research on the community and relevant prior work, and identify key stakeholders that the team should interact with during the assessment (Darcy & Hofmann, 2003; Kretzmann & McKnight, 1993; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010). Several frameworks exist to help designers plan and organize this contextual research (e.g., Aranda-Jan et al., 2014; Baillie et al., 2010; Wood & Mattson, 2016). During the pre-assessment phase, the team should also develop their data collection tools, including interview protocols and observation frameworks, and identify potential screening criteria for future needs filtering (Darcy & Hofmann, 2003; Kretzmann & McKnight, 1993; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010).

Figure 4.1 Overview of needs assessment process (adapted from content in Watkins et al. (2012) and Witkin & Altschuld (1995))



Once pre-assessment activities have been completed, the team begins the assessment. During the assessment phase, the team should employ a range of qualitative and quantitative research methods, such as interviews, observations, surveys, and focus groups, to collect data from stakeholders that might be used to identify needs (Darcy & Hofmann, 2003; Kretzmann & McKnight, 1993; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010). While the team collects data, they should also perform preliminary analyses to verify the quality of the data being collected and identify initial needs that may drive iterations on the team's data collection approach (Darcy & Hofmann, 2003; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010). The team may also use these data to iterate on their initial screening criteria (Watkins et al., 2012; Zenios et al., 2010). The assessment phase ends after the team has performed rigorous qualitative and/or quantitative analyses on the full data set to identify recurring trends and/or themes that correspond to community needs (Darcy & Hofmann, 2003; Kretzmann & McKnight, 1993; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010).

Finally, during the post-assessment phase, the team should continue to refine their definitions of identified needs to ensure that addressing these needs will have the intended outcomes for stakeholders (Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010). The team should then filter these needs based upon a finalized set of screening criteria to identify which needs the team and/or their partner community or organization could most feasibly address (Darcy & Hofmann, 2003; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010). Based on this final list of prioritized needs, the team should develop a plan of action and report this plan to their partner (Darcy & Hofmann, 2003; Kretzmann & McKnight, 1993; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995). By the end of the post-assessment phase, the team should be able to justify committing substantial resources to future action through comprehensive descriptions of community or organizational needs (Altschuld et al., 2014; Darcy & Hofmann, 2003; Kretzmann & McKnight, 1993; Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Watkins & Kavale, 2014; Witkin & Altschuld, 1995; Zenios et al., 2010).

4.2.2 Needs assessment best practices

Several needs assessment best practices (summarized in Table 4.1) have been suggested across disciplines.

Table 4.1 Needs assessment best practices identified from the needs assessment literature

Best practices	References	Definition
Identify how own subjectivity influences process	(Darcy & Hofmann, 2003; Kretzmann & McKnight, 1993; Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Zenios et al., 2010)	Identify how the team's collective expertise and previous experiences may influence the team's perspective on needs and approach to conducting a needs assessment
Collect many different types of data	(Darcy & Hofmann, 2003; Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010)	Collect and compare conclusions across many different types of data, such as interviews, observations, surveys, and focus groups
Select data collection methods based on specific criteria	(Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995)	Select data collection methods that are well-suited to the goals of the needs assessment and appropriate for stakeholders
Interact with a wide variety of stakeholders	(Darcy & Hofmann, 2003; Kretzmann & McKnight, 1993; Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010)	Solicit input from many different stakeholder groups in the community or organization
Develop rigorous metrics to evaluate and prioritize needs	(Darcy & Hofmann, 2003; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010)	Develop consistent standards of comparison to evaluate the reliability and relevancy of identified needs and determine which needs to address first
Engage community or organization as equal partners	(Altschuld et al., 2014; Kretzmann & McKnight, 1993; Martí-Costa & Serrano-García, 1983; Watkins et al., 2012; Zenios et al., 2010)	Engage the partner community or organization as equal participants in the needs assessment process to build partner capabilities and support the partner in addressing identified needs

Needs assessment teams should be mindful of their own subjectivity as practitioners to avoid biasing their needs assessment process (Darcy & Hofmann, 2003; Kretzmann & McKnight, 1993; Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Zenios et al., 2010). Reflexivity is necessary because a team's perspective on “needs” will influence their approach to data collection and analysis (Darcy & Hofmann, 2003; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Watkins & Kavale, 2014). For example, teams that define needs only as deficits might overlook the unique strengths of the partner community or organization that could be leveraged to address identified needs (Sleezer et al., 2014; Kretzmann & McKnight, 1993; Martí-Costa & Serrano-García, 1983; Watkins & Kavale, 2014; Altschuld et al., 2014). In a cross-cultural context, a designer’s outsider perspective may also bias their perception of the root political or economic conditions that give rise to stakeholder needs (Aslam et al., 2014; Leydens & Lucena, 2018; Nieusma & Riley, 2010).

Needs assessment teams should collect many different types of data (Darcy & Hofmann, 2003; Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010). This recommendation arises because each data source has inherent limitations; for instance, stakeholders may have trouble verbalizing implicit knowledge during interviews (Rosenthal & Capper, 2006; Sutcliffe & Sawyer, 2013). In the qualitative and mixed methods literature, this best practice is often referred to as “triangulation” (Leydens et al., 2004; Creswell & Plano Clark, 2018; Maxwell, 2013; Borrego et al., 2009; Patton, 2015). By comparing the differences in conclusions that might be drawn from different data sources or data collection approaches, a needs assessment team might address potential validity threats related to their interpretations of community needs.

Needs assessment teams should select their data collection methods based upon specific criteria related to the goals of the needs assessment and qualities of community or organization stakeholders (Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995). Teams should be able to justify that the data collection methods they select are well suited for eliciting useful information related to the assessment because these methods determine the content, reliability and validity of the information that the needs assessment team may uncover (Borrego et al., 2009; Creswell & Plano Clark, 2018; Maxwell, 2013; Patton, 2015; Spradley, 1979). For example, designers in cross-cultural design contexts might chose to employ visual tools and representations (e.g., (Ambole et al., 2016; Aslam et al., 2013; IDEO, 2015)) as part of their data collection approach due to the difficulties associated with communicating verbally across language barriers.

Needs assessment teams should collect data from a wide variety of stakeholders (Darcy & Hofmann, 2003; Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010). This breadth serves as another form of triangulation that can help teams develop valid descriptions of community needs (Borrego et al., 2009; Creswell & Plano Clark, 2018; Leydens et al., 2004; Maxwell, 2013; Patton, 2015). Furthermore, teams should interact with a wide variety of stakeholders because each stakeholder group in a community or organization may experience the same need differently; while addressing a given need may have a positive impact on one group, it could also have a negative effect on another group (Darcy & Hofmann, 2003; Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010). Interacting with a wide variety of stakeholders is thus necessary to understand the benefits and consequences of potential action and to identify the full range of relevant stakeholders who might be affected.

Needs assessment teams should develop valid and consistent metrics to evaluate and prioritize identified needs (Darcy & Hofmann, 2003; Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010). These metrics can help ensure that needs assessment teams are making wellfounded judgments about which needs should be addressed. Needs filtering metrics should take into account the potential impacts of addressing a given need, the needs assessment team or partners' capabilities to address the need, and the team or partners' motivations to address the need (Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010). Evaluating needs according to these metrics can help the team and their partner community or organization determine how they can best allocate available resources in order to achieve tangible positive outcomes with the partner.

Finally, needs assessment teams should engage the partner community or organization as equal participants in the needs assessment process to build partner capabilities and support the partner in both addressing current needs and identifying future needs (Altschuld et al., 2014; Kretzmann & McKnight, 1993; Martí-Costa & Serrano-García, 1983; Zenios et al., 2010). The needs assessment team should be transparent with their partner community or organization about their needs assessment process and the data they are collecting, check with partners to validate initial conclusions, and involve partners in making decisions based on assessment findings. Participatory data collection techniques (e.g., (Aslam et al., 2013; Girón et al., 2004; Hussain et al., 2012; Kang, 2016)) may also be effective for engaging the partner community or organization and building partner capabilities.

4.2.3 Needs assessments in the context of cross-cultural student projects

Undergraduate engineering students are increasingly participating in, and in many cases leading (e.g., Harshfield et al., 2009; de Chastonay et al., 2012; Magoon et al., 2010; McDaniel et al., 2011), cross-cultural, community-oriented design projects involving the identification of needs and the subsequent development of solutions to address a subset of the identified needs. These projects take place in both curricular and co-curricular settings, such as design courses with an international development focus or international service-learning projects. Previous studies suggest that participating in cross-cultural design projects can help engineering students develop skills for cross-disciplinary communication and teamwork (Sienko et al., 2018; Gordon et al., 2018; Gutierrez Soto & Dzwonczyk, 2015; Jeffers et al., 2015), cross-cultural communication (de Chastonay et al., 2012; Harshfield et al., 2009; Jeffers et al., 2015; Sienko et al., 2018; Viswanathan & Sridharan, 2012), adaptive problem-solving (Garff et al., 2013; Gordon et al., 2018; Jeffers et al., 2015; Sienko et al., 2018; Viswanathan & Sridharan, 2012), design ethnography (Sienko et al., 2018; Viswanathan & Sridharan, 2012), reflection (Harshfield et al., 2009; Lemons et al., 2011; Viswanathan & Sridharan, 2012), and management of ambiguity due to limited information (Budny & Gradoville, 2011; Lemons et al., 2011). Each of these skills may be helpful for identifying and evaluating needs in cross-cultural settings.

However, while cross-cultural design experiences benefit engineering students, there are several examples of projects failing to produce successful design outcomes for the partner community. In many cases, these project failures are due to students lacking an adequate understanding of community needs and the broader context of their projects (Harshfield et al., 2009; LaPorte et al., 2017; Mazzurco & Jesiek, 2014; Wood & Mattson, 2016). Students may frequently struggle to understand community needs because instruction relating to needs assessments and community engagement is not part of standard undergraduate engineering curricula (Sienko et al., 2018; Leydens & Lucena, 2014; Vanasupa et al., 2006; Schneider et al., 2008; Baillie et al., 2010); students may consequently encounter difficulties when trying to identify and evaluate needs in their partner community (Aslam et al., 2014; Harshfield et al., 2009; Wood & Mattson, 2016). Furthermore, the short time frame of many projects involving students (e.g., the projects described in Harshfield et al. (2009) and Klopfenstein et al. (2011), both of which implemented solutions roughly a year after first establishing their respective community partnerships) may hinder the ability of students to engage deeply enough in needs assessment to develop and implement robust solutions.

The majority of studies involving engineering students in cross-cultural settings have described situations where students iterated on or generated solutions for needs that had already been identified. While a few studies have discussed situations where students contributed to the initial identification of needs (e.g., Bargar et al., 2016; Sienko et al., 2018; Tendick-Matesanz et al., 2015; Young et al., 2016), these accounts focused on the community need that was ultimately identified rather than the specific competencies students employed to identify needs or choose a project direction.

4.3 Methods

4.3.1 Research questions

This study sought to understand what an undergraduate engineering student team knew about conducting needs assessments and how their knowledge changed as a function of conducting a needs assessment. We also wanted to explore the challenges that engineering students may encounter as part of conducting needs assessments. Our study was thus guided by the following research questions:

1. What do engineering students think are best practices for conducting needs assessments?
2. How do student perspectives on these best practices change as a result of conducting a needs assessment?
3. What challenges do engineering students encounter when conducting needs assessments? How do these challenges affect student processes?

4.3.2 Design context

Data for this study were collected from a team of twelve students who conducted a needs assessment in a rural South American community (the "partner community"). The needs assessment was sponsored by an undergraduate co-curricular organization that specialized in medical device design for low-resource settings. The organization had sponsored several needs assessments in the past and used the term "needs assessment" to describe these endeavors. This needs assessment was the organization's first in this specific partner community; the organization's goal was to establish local partnerships and identify needs that might form the basis for future co-curricular projects. This study focused primarily on the pre-assessment (7 weeks) and assessment (1 week) phases of the team's needs assessment.

As part of the team's pre-assessment phase, the team completed training related to conducting observations, conducting a needs assessment, and developing needs statements through the University of Michigan's Center for Socially Engaged Design (C-SED) (*Socially Engaged Design Academy*, n.d.). C-SED offers a variety of training modules related to employing design ethnography methods such as interviews and observations, analyzing stakeholder data to develop needs statements and user requirements, and generating creative solutions to design problems. These modules are completed individually and blend an online review of best practices with in person practice and coaching (Young et al., 2017). Each module includes prior knowledge reviews, content quizzes, practice application tasks, and reflections that in total typically take around five hours per person to complete. The three topics that participants covered were selected by the team's leadership as the highest priority topics based upon the activities that the team expected to perform while in the partner community. Content included in the needs assessment module drew heavily from the recommended practices described in Zenios et al. (2010), Watkins et al. (2012), and Royse et al. (2009).

The team's assessment phase involved a one-week service-learning experience organized in collaboration with a local partner non-profit organization (the "partner organization"). While in the partner community, the team spent several hours each day conducting observations of community medical centers and interviewing local villagers. The team was aided by two individuals from the partner organization (hereafter referred to as "the guides"). One guide was from the community where the team was collecting data. The other guide was the same nationality as the team but had lived in the community for some time. While in the community, the team split into two main sub-groups to interact with as many stakeholders as possible. The team then reconvened each night to discuss the data they had collected thus far, reflect on their experiences, and plan what data they wanted to collect during the next day.

4.3.3 Participants

Demographic information for the twelve members of the needs assessment team are shown in Table 4.2 (names are pseudonyms). Qualitative work often involves deep exploration of select samples or cases to facilitate identification of elements from participant experiences that may be transferable to similar contexts (Borrego et al., 2009; Patton, 2015); the sample size of this study is in alignment with other similar qualitative longitudinal studies of student cross-cultural design experiences (e.g., Budny & Gradoville, 2011; Garff et al., 2013; Harshfield et al., 2009; Jeffers et al., 2015). Participants generally had one to three semesters of curricular design experience, depending upon their year and program. Several participants also had six to eighteen months of co-curricular and/or internship design experience, particularly through the co-curricular organization that was sponsoring the needs assessment. None of the participants had conducted a needs assessment as part of their previous design experiences, although one of the two team leads, Alli, had previous experience employing design ethnographic methods such as interviews and observations to collect in-depth information from users.

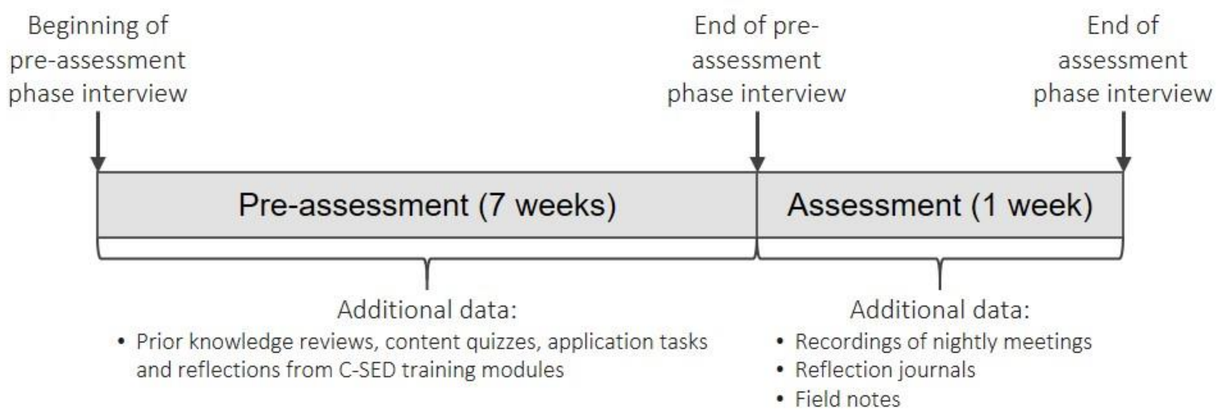
Table 4.2 Participant demographics

Pseudonym	Year	Sex	Race/Ethnicity	Primary Major	Secondary Major/Minor
John	Freshman	M	White	Public Health	
Emma (Lead)	Master's	F	White	Biomedical Engineering	
Isabelle	Sophomore	F	Asian	Chemical Engineering	
Sophie	Freshman	F	Asian	Biomedical Engineering	
Jill	Sophomore	F	White	Industrial Engineering	International Minor for Engineering
Stephanie	Junior	F	Asian & White	Biomedical Engineering	American Culture
Chloe	Freshman	F	White	Biomedical Engineering	
Maria	Freshman	F	Hispanic	Public Health	Spanish
Emily	Sophomore	F	Asian & White	Mechanical Engineering	Music
Melissa	Freshman	F	Asian	Biomedical Engineering	Creative Writing
Arya	Freshman	F	Asian	Electrical Engineering	Business
Alli (Lead)	Junior	F	White	Mechanical Engineering	Multidisciplinary Design

4.3.4 Data collection

Participants completed three semi-structured group and individual interviews with a member of the research team: a “beginning of pre-assessment phase” interview, an “end of pre-assessment phase” interview, and an “end of assessment phase” interview. The timeline for these three interviews is shown in Figure 4.2. The “beginning of pre-assessment phase” interview occurred before the team had begun in-depth pre-assessment activities and training and explored participants’ perceptions about conducting observations, conducting needs assessments, and developing needs statements based on their previous design experiences. The “end of pre-assessment phase” interview occurred immediately before the team disembarked to conduct assessment activities in their partner community and focused on how participants might use what they had learned about observations, needs assessments, and needs statements when collecting and analyzing their data. The “end of assessment phase” interview occurred after the team returned from the partner community. During the end of assessment phase interview, participants were asked to describe lessons learned from the experience, how they had applied the best practices learned during their pre-assessment training, and challenges encountered when collecting data in the community. Beginning and end of pre-assessment phase interviews occurred in four groups of three team members so that participants could elaborate on each other's responses. The composition of these four groups was the same for both interviews. Participants completed end of assessment phase interviews individually to allow the researchers more space to explore individual experiences.

Figure 4.2 Data collection timeline



Interview protocols were developed for each interview following recommended protocol development practices (Creswell & Plano Clark, 2018; Leydens et al., 2004; Maxwell, 2013). Since each interview explored participant perspectives on conducting observations, conducting needs assessments, and developing needs statements, the interview protocols provided a structured way to explore each topic in depth. Sample questions from the needs assessments portion of each protocol are shown in Table 4.3; these questions provided a starting point that prompted in-depth stories and examples from participants. When developing the beginning of pre-assessment phase interview protocol, we iterated on our questions by piloting the protocol with other undergraduate students who had similar relevant experiences. While we did not pilot the end of pre-assessment phase and end of assessment phase protocols, we kept track of participant experiences during their pre-assessment and assessment activities to ensure that our questions remained relevant to these experiences. For instance, the end of assessment phase protocol originally followed the observations, then needs assessments, then needs statements structure of the earlier two protocols. However, given the team's extensive reliance on stakeholder interviews once in the community, this end of assessment phase protocol was changed to a general data collection, then needs assessments, then needs statements structure instead.

Table 4.3 Examples of questions pertaining to needs assessments asked during researcher interviews

	Questions
Beginning of pre-assessment phase interview	Why might designers or engineers conduct needs finding activities? What prior experiences do each of you have with needs finding activities? Based upon your prior experiences, how do you think you might conduct needs finding activities during your trip?
End of pre-assessment phase interview	Based upon your preparation, how do you think you might approach this needs assessment? In addition to what we have discussed with observations, what do you think you might want to do to help the experience go well? What best practices do you think the [modules] were emphasizing most relating to needs assessments? Beyond those discussed regarding observations, what challenges do you anticipate encountering when conducting a needs assessment in [the community]?
End of assessment phase interview	Thinking across the experience as a whole, how do you think your needs assessment trip went? In addition to data collection, what are some things that you or your team did that you think helped your needs assessment experience go well? Which key takeaways about needs assessments from the [module] do you think you applied well? What about takeaways that were more difficult to apply? What other challenges did you encounter when conducting needs assessment activities in the field? What do you think you learned about conducting needs assessments from this experience?

Recordings of participant interviews (11 hours of audio) were transcribed to facilitate data analysis. In addition to the three interviews completed by each participant, we also collected other types of data, including submissions completed as part of the C-SED modules and individual assessment phase reflection journals where participants described how their activities aligned with needs assessment best practices. Each participant also submitted field notes from their assessment activities, and team leaders submitted recordings of the team's nightly assessment phase planning discussions. Team nightly discussions represented four hours of audio, while journal entries, field notes, and C-SED module submissions represented over one hundred pages of writing. We used these additional data to verify that participant interview responses accurately reflected participant perspectives on their pre-assessment and assessment activities (Borrego et al., 2009; Creswell & Plano Clark, 2018; Leydens et al., 2004; Maxwell, 2013). Prior knowledge reviews from C-SED modules helped verify participant responses from beginning of pre-assessment phase interviews. Reflections from C-SED modules helped verify participant responses from end of pre-assessment phase interviews. The team's nightly discussions, individual reflection journal entries and field notes helped verify participant responses from end of assessment phase interviews.

4.3.5 Data analysis

Two coders reviewed the transcripts of participant interviews several times to familiarize themselves with the data. These two coders then identified and described distinct participant responses to the needs assessment questions shown in Table 4.3. Responses were grouped thematically to develop an initial set of key themes that represented common team conceptions of needs assessment best practices as well as identified challenges (Creswell & Plano Clark, 2018; Miles et al., 2014; Patton, 2015). Once this set of initial themes was defined, the two coders returned to the transcripts and identified additional responses that had been overlooked during the first round of analysis. The two coders discussed discrepancies in their respective interpretations of the themes that had been identified, iterated on the definitions of these themes, and settled on a final set of codes. NVivo 12, a qualitative analysis software, facilitated organization of our data during data analysis. The complete set of identified themes is discussed in Section 4.4.

4.4 Findings

Findings are presented below in five sub-sections. Section 4.1 outlines participant conceptions of best practices for conducting needs assessments at the beginning their pre-assessment phase. Sections 4.2 and 4.3 describe participant conceptions of best practices at the end of the team's pre-assessment and assessment phases, respectively. Section 4.4 summarizes challenges that the team anticipated for their assessment phase after completing their pre-assessment activities and training. Section 4.5 discusses challenges that the team encountered during their assessment phase.

4.4.1 Participant conceptions of needs assessment best practices reported at the beginning of the team's pre-assessment phase

Participant conceptions of needs assessment best practices reported during beginning of pre-assessment phase group interviews are listed in Table 4.4 in order of prevalence.

Table 4.4 Participant conceptions of needs assessment best practices reported during beginning of pre-assessment phase group interviews

Conceptions of needs assessment best practices	# of groups (of 4)	Definition	Example
Keep an open mind	4	Keep an open mind and avoid making assumptions about community needs	*Maybe just keep an open mind about needs. Even if something seems like it's fine at face value, there still might be a need there, but… don't be trying too hard to make mountains out of molehills.* (Melissa)
Follow up with stakeholders	4	Follow up with stakeholders to check the validity of preliminary conclusions	*Just observing probably wouldn't be enough. Like also talking and observing something and being like, 'hey, I'm noticing this, is this something that's always like this, like is it a problem for people?' Getting some sort of perspective to your observations…* (Emily)

Identify potential needs in advance	2	Have an idea in advance of what types of needs may exist in the community	*In being prepared, I think we need to arrive there with some idea of what we're looking for, not just like, 'Oh, what's going on?'… Kind of milling with the scope of things that we can bring back to [our organization]* (Stephanie + Jill)
Don't cross boundaries	1	Don't cross boundaries to avoid offending stakeholders	*I feel like it's going to be more observation based than interaction based because, not crossing boundaries… Making sure we don't offend the people we're observing because it is a medical clinic… People are coming in here when they're vulnerable.* (Maria + Emily)
Let stakeholders guide conversation	1	Give stakeholders space to talk about the topics that are most important to them to help uncover root needs	*I'd say it's important to keep questions really broad and let the person you're talking to steer the conversation the way that's most important to them, because that's how you'll get at the root need that they have.* (Alli)
Conduct research to understand culture	1	Conduct prior research to learn about the culture of the community	*…Read up as much as [you] can and gain as much information as [you] can before [you] go somewhere totally new. Because once again it goes back to the whole idea, you should be well aware of what their environment and their culture is like.* (Chloe)
Communicate within team	1	Communicate within the team to make sure all team members have necessary information	*Prepare and communicate with the other [planning] sub teams as well, so we have all the information that we need.* (Sophie)
Visit other places and compare data	1	Collect data from different locations to compare with data collected during the needs assessment	*I think something we could do… just to have a comparison is to visit other places... Maybe not in [the same country], but once we're done there, go somewhere else and see what [others] are doing compared to what [the community] were doing.* (Chloe)

The two most common themes – *Keep an open mind* and *Follow up with stakeholders* – summarize the team's collective perspective on needs assessment best practices at the start of their pre-assessment phase. In the case of *Keep an open mind*, participants discussed the mindsets they would adopt to avoid biasing their perception of needs:

"Just keep an open mind about needs. Even if something seems like it's fine at face value, there still might be a need there, but… don't be trying too hard to make mountains out of molehills." (Melissa)

Melissa felt that designers navigate two different challenges when perceiving needs. On one hand, designers might see situations that appear satisfactory but would reveal deeper issues with further probing. On the other hand, designers might see situations that initially seem problematic but are not substantial issues for stakeholders. *Keeping an open mind* can help designers avoid letting their assumptions cloud their perception of community needs.

All four participant groups also discussed the need to *Follow up with stakeholders* to check the validity of the conclusions they were drawing from their data, for example:

"We're working with a non-profit when we go there, so those are people that are familiar with the environment. Just observing probably wouldn't be enough. Like also talking and observing something and being like, 'hey, I'm noticing this, is this something that's always like this, like is it a problem for people?' Getting some sort of perspective to your observations because as a person who doesn't know much about the environment, it's really useful to have that sort of input outside of just what you see." (Emily)

Emily stressed that observational data alone would likely be insufficient and that designers should compare their initial conclusions about potential needs to community perspectives on those needs. Her rationale was that her team did not have much contextual knowledge about the community, so stakeholder perspectives would likely be needed to provide greater context into the needs that the team was identifying. While Emily singled out the team's non-profit partner organization as a key group to follow up with, other participants also discussed following up with clinicians in the community health centers or other members of the community.

While discussing these two specific best practices, participants often referred to their previous education and experiences for justifying their suggestions. For example, many of the participants described being exposed to case studies of failed design projects through their curricular and co-curricular experiences:

"I feel like there are many instances of engineers… trying to define for others what they think the needs are. If any of you guys were at the design showcase, the one story about the filter straw? They saw a need for filtered water, and because they didn't do a needs assessment they made a filter straw, which was very culturally insensitive because they were imagining [their users] would take the straw and drink from the dirty river and it was a really bad needs assessment. I mean, there may have been an actual need for water filtration but that wasn't the correct way to go about it. I think it's important to hear from the people that you're actually trying to assist, hear what they actually want assistance on..." (John)

By referring to the example of the filter straw, John highlighted a concrete situation where designers made inaccurate assumptions about stakeholder needs because they did not conduct an effective needs assessment. While the base need (access to clean water) was legitimate, the design team did not adequately explore all relevant factors when defining this need and their solution failed as a result. For John, the main takeaway of this example was that the design team should have engaged more with their stakeholders. In other words, designers should *Keep an open mind* when conducting needs assessments and can do so by *Following up with stakeholders* to verify conclusions.

4.4.2 Participant conceptions of needs assessment best practices reported at the end of the team's pre-assessment phase

Participant conceptions of needs assessment best practices reported during end of pre-assessment phase group interviews are listed in Table 4.5 in order of prevalence. Compared to the beginning of pre-assessment phase interviews, there were no end of pre-assessment phase conceptions that appeared consistently across all four participant groups. This relative lack of consistency may have been because each participant focused on different key takeaways while completing the C-SED needs assessment module (hereafter, "the C-SED module").

Table 4.5 Participant conceptions of needs assessment best practices reported during end of pre-assessment phase group interviews

Conceptions of needs assessment best practices	# of groups (of 4)	Definition	Example
Justify identified needs	3	Justify descriptions of identified needs based on available data	*There's so much depth to the number of people that are involved... and how prominent that certain problem is… What you see isn't always the need, there might be something… deeper that you may have to find.* (Emily)
Follow up with stakeholders	3	Follow up with stakeholders to verify that identified needs correspond to true community needs	*…any way that we can try to get from them what they think is important… what they think could change would be really helpful… because they are the ones dealing with this clinic every day. We're only there for a week. We can't see everything.* (Jill)
Conduct research to help build rapport	2	Researching the culture of the community in advance will help with building rapport	*Just making the small efforts to understand or know something about their culture beforehand right when you get there, it really shows that you've made an effort and that you're here to talk to them.* (Isabelle)
Have a plan	2	Develop a detailed plan in advance for conducting a needs assessment	*I think that our needs assessment is going to be much more organized and structured. I think we're going to definitely incorporate some of the frameworks that we… learned from [the C-SED modules].* (Maria)
Identify questions to ask	1	Think of potential questions to ask stakeholders before entering the community	*I don't think having really strict interview protocols is important, but maybe just having an idea of the types of questions you'd want to ask so that you have more of a… reading to start with… and then conversations kind of go where they go.* (Alli)

Be solution neutral	1	Focus on needs rather than potential solutions	*Don't focus on the solution…You have to focus on the actual need and where the gap in productivity would be.* (Jill)
Avoid offending stakeholders	1	Avoid unintentionally offending stakeholders while collecting data	*…We're there to do design observations and a needs assessment, but don't get so caught up in that that we also offend the clinicians by getting in their way. 'Cause we're there for one task, but they're also still trying to do their jobs…* (John)
Identify appropriate scope of needs	1	Identify the scope of needs that the team can address	*They also talked about the scope and how much… we can actually handle, so that would help with building things.* (Sophie)

One of the more common themes – *Justify identified needs* – focused on how designers should consider community context when describing needs and justify that descriptions of needs are supported by data. As Emily explained:

"Before I [thought] you're just going to be looking at something and say, 'Okay, what does this person need right now?' It's way more than that. There's so much depth to the number of people that are involved... and how prominent that certain problem is. I think it'll help me to think beyond just what you see. What you see isn't always the need, there might be something… deeper that you may have to find." (Emily)

Initially, Emily thought that identifying needs would be as simple as observing a stakeholder in a certain situation and identifying potential deficiencies. However, after completing the C-SED module, she realized that needs are complicated and that everyone experiences needs differently: what may be a problem for one stakeholder may not be a problem for another. Emily also emphasized that there are different types of needs. While designers might identify surface needs based on observations, many times there are also deeper needs that designers may need to uncover. Several other participants also referred to different ways of categorizing needs, such as needs that could be addressed with available resources compared to needs that might require radical innovations.

Participants again emphasized the importance of *Following up with stakeholders* and reiterated many of the same points made in the beginning of pre-assessment phase interviews, including that this practice can help ensure that needs identified by the team corresponded to true needs in the community. During end of pre-assessment phase interviews, participants also emphasized that this best practice was especially relevant in their case since they would be in the community collecting data for a relatively short amount of time. As Jill described:

"I don't think we'll be able to have formal interviews with [our stakeholders], but any way that we can try to get from them what they think is important… what they think could change would be really helpful towards the needs assessment because they are the ones dealing with this clinic every day. We're only there for a week. We can't see everything." (Jill)

As in her beginning of pre-assessment phase interview, Jill emphasized that soliciting stakeholder perspectives on needs would significantly benefit the team's needs assessment process. However, in this case, Jill also explicitly referred to how the time constraints of the team's assessment phase were going to limit the data that the team could collect. Jill thus felt that stakeholders could provide valuable input in describing aspects of community needs that the team would not have time to observe directly. Several participants also discussed the need to plan out these follow up activities as part of the team's nightly discussions.

4.4.3 Participant conceptions of needs assessment best practices reported at the end of the team's assessment phase

Participant conceptions of needs assessment best practices reported during end of assessment phase individual interviews are listed in Table 4.6 in order of prevalence.

Table 4.6 Participant conceptions of needs assessment best practices reported during end of assessment phase individual interviews

Conceptions of needs assessment best practices	# of students (of 12)	Definition	Example
Account for diverse perspectives	12	Account for diverse stakeholder perspectives to understand community needs in greater depth	*Going to all the different communities was great because we got to hear different perspectives, which also helped us get a more holistic view.* (John)
Leverage local connections	10	Leverage local connections to build rapport in the community	*If you are doing a needs assessment in a more remote, foreign, completely different cultural area, it's important to use something that's already there to implant yourself.* (Stephanie)
Compare data across team	9	Share observations and interpretations across team members to compare different perspectives	*Even though we often were together as a group, how we perceived that experience, and what observations we were making, were very different amongst us. I think having the opportunity to share… and bounce ideas off each other was extremely helpful.* (Maria)
Avoid biasing data collection	5	Avoid embedding opinions or solutions when collecting data	*I think being objective... Making sure I'm not putting my opinions in what we're doing. Then, also not trying to target anything towards solutions.* (Jill)
Keep an open mind about needs	5	Keep an open mind about potential community needs	*If you go in with a narrow perspective… you might be missing a lot of things… We knew we wanted to do something health care related, but then there's education and government and… all of those things are related, so just don't go in with a narrow mindset.* (Emily)
Adopt flexible data collection approach	3	Adapt data collection approach to changing circumstances during stakeholder interactions	*When the conversation would go off, I could still come up with new things I wanted to learn about… because there was so much information that we needed to know. I felt that I wasn't stuck on any one thing.* (Alli)
Take good notes	3	Record notes in enough detail to justify the needs identified by the team	*Taking good notes was a big thing. If you don't have good observations, you can't do good needs assessment and you can't do good need iteration.* (Emma)

The needs assessment best practice most commonly cited by participants was *Account for diverse perspectives*. Participants discovered during their assessment activities that their stakeholders all had individual perspectives on potential community needs; the team thus felt that they needed to explore these different perspectives in order to understand which needs in the community were most relevant. As described by John:

"Going to all the different communities was great because we got to hear different perspectives, which also helped us get a more holistic view, because I know for example, one woman we talked to said the greatest problem was their ineffective community leaders. But then we heard from our [guide] that was likely due to the fact that she was [a religious minority]. Her religion distanced her from the rest of the community, so it was like her personal factors. In speaking with other community members, we found that certainly was not the most pertinent issue. It was very beneficial, though, that we got a wide range of perspectives." (John)

As John discussed, the team encountered divergent opinions from stakeholders relating to potential community needs, in this case the ineffectiveness of community leaders. The team found that one woman, who happened to be a religious minority, possessed a substantially different view on this need than the other members of the community. By interacting with a variety of different stakeholders, the team realized that this need, while important to this individual woman, was not a priority for the majority of community members.

Participants also felt that working closely with key stakeholders, such as their guides, helped the team conduct their needs assessment. Participants frequently cited *Leveraging local* *connections* as an important practice to build initial rapport with stakeholders. As Stephanie described:

"We would not have been able to do a lot of those things if we didn't have access to our tour guides. It would've been so much harder to just get yourself into a community. If you are doing a needs assessment in a more remote, foreign, completely different cultural area, it's important to use something that's already there to implant yourself… if we had just showed up and knocked on these people's doors, and were like, "Hey, I wanna ask you a few questions," they probably would've said no, and then there would've been a huge language barrier… I guess, being really prepared for that kind of stuff is just the most important." (Stephanie)

Stephanie recognized that the team's guides played a key role in helping the team interact with the community. The team's guides lived in the community and were well known to many of the individuals with whom the team interacted; they thus proved to be a valuable resource for making contacts and building relationships. The guides further facilitated these interactions by acting as translators for the team. By *Leveraging local connections*, participants felt that they were able to build rapport and communicate with their stakeholders more successfully than they might have been able to otherwise.

Nine of the twelve participants highlighted how being part of a cross-disciplinary team with many diverse perspectives benefitted the team's assessment activities. By *Comparing data across the team*, team members felt that they were better able to understand how their own individual perspectives influenced how they perceived their data. The following excerpt provides a typical account:

"I would definitely say the daily debrief sessions were a huge help. Without that opportunity to hear what other people were thinking and get other individual takes on the same situation, I think we would have missed out on a lot of observations and potential needs statements. Even though we often were together as a group, how we perceived that experience and what observations we were making was very different... I think having the opportunity to share with other individuals and bounce ideas off each other was extremely helpful." (Maria)

Maria felt that without the diversity of perspectives among team members, the team would likely have missed out on several surprising insights while in the community collecting data. Even though team members often conducted observations and interviews in groups together in the same location, Maria highlighted how team member perceptions of those experiences were very different. Participants claimed that comparing different perspectives and ideas thus helped their team identify their individual biases, and that discussing these biases led the team to identify new needs from their data that they might have missed otherwise.

4.4.4 Needs assessment challenges described at the end of the team's pre-assessment phase

The needs assessment challenges described by participants during end of pre-assessment phase group interviews are listed in Table 4.7 in order of prevalence. These challenges related to difficulties that participants expected to encounter during their assessment phase activities. Four themes, *Overcoming team biases*, *Optimizing short time in community*, *Managing extensive data*, and *Navigating language barriers*, described anticipated challenges directly. Two themes, *Practicing assessment skills* and *Finding contextual information*, described challenges encountered during pre-assessment activities that participants felt might impact their assessment phase.

Table 4.7 Challenges described during end of pre-assessment phase group interviews

Needs assessment challenges anticipated	# of groups (of 4)	Definition	Example
Overcoming team biases	3	The team has collective biases that may influence the objectivity of the needs assessment	*We all have higher education. We're all from [Midwestern University]. We all have specific subjectivity as a group, so I think avoiding that is something that's gonna be a hard challenge for us all.* (Emma)
Practicing assessment skills	2	The team had limited opportunities to practice conducting a needs assessment	*Practice is always helpful. We haven't done a ton of that other than the application [task].* (Jill)
Finding contextual information	2	The team struggled to find additional information about the specific community	*We don't exactly know what we're going to be doing today. It's hard to prepare… since we don't have that information [on the clinics] available to us. We can really only do research about the culture…* (Jill)
Optimizing short time in community	2	The team will have a very short amount of time in the community to collect data	*I think that the time constraint that we have might also make it kind of difficult. We are only there for a week, but that week is ... There's a significant chunk taken out of that week due to travel.* (Stephanie)
Managing extensive data	1	The team may struggle to manage the substantial quantity of data that they plan to collect	*Just finding an effective way to go through the copious amount of notes that we'll have without losing objectivity or without making [the data] less effective… finding a way to make it more manageable.* (John)
Navigating language barriers	1	Due to the language barrier, the team may struggle to understand the nuances of stakeholder responses	*I think the language barrier is gonna be something because even though I know a little bit of Spanish and all of that I don't think I know enough to pick up on the nuances of their language…* (Melissa)

The most common anticipated challenge described by participants was *Overcoming team biases* that might influence how the team perceived community needs during data collection. As one participant described:

“We all have higher education. We're all from [Midwestern University]. We all have specific subjectivity as a group, so I think avoiding that is something that's gonna be a hard challenge for us all.” (Emma)

Emma highlighted participants’ higher education and shared university context as factors that might contribute to collective biases that the team may struggle to identify and overcome. Other team members also emphasized that their lack of familiarity with the community’s health care system might bias their perception of potential needs and that as engineers they had a bias towards embedding solutions in identified needs.

4.4.5 Needs assessment challenges described at the end of the team’s assessment phase

The needs assessment challenges reported by participants at the end of their assessment phase are listed in Table 4.8 in order of prevalence. Four challenges, *Understanding the context, Optimizing short time in community, Executing recommended practices from training* and *Navigating language and cultural barriers,* were anticipated by participants but had implications that only became clear for participants during their assessment phase. The other four challenges, *Accessing stakeholders, Recording data during fast-paced interactions, Evaluating needs,* and *Identifying appropriate needs,* were discovered by participants while completing their assessment activities.

Table 4.8 Challenges described during end of assessment phase individual interviews

Needs assessment challenges encountered	# of students (of 12)	Definition	Example

Understanding the context	11	The team struggled to optimize data collection activities based on limited understanding of the community context	*I felt like if we had been given slightly more information about what part of the river we were going to or had done more general research, we would've been able to target our questions more from the beginning...* (Jill)
Optimizing short time in community	10	The team had limited time in the community, which limited the amount of information they could collect	*…at the end of the week, I noticed that we had our needs statements, but even then from there I knew we had very little information.* (John)
Accessing stakeholders	7	The team did not have access to several relevant stakeholder groups	*We talked to a lot of people in the community and maybe one person who's actually in the community government, and we didn't get anyone who was higher up in that spectrum, so everything was from a very one class point of view.* (Emily)
Recording data during fast-paced interactions	4	The pace of stakeholder interactions made it difficult for the team to collect quality data	*You're trying to write things down and there's something else happening over there because someone's asking another question… I think out in the field, it moves a lot faster than I was expecting. It's a lot harder to do everything and to get it all done well.* (Alli)
Evaluating needs	3	The team struggled to evaluate the relevance of identified needs in the community	*I think determining if it's a need or not was very hard… You see someone in such poverty… Remembering that maybe it is not a need necessarily for them, but something that you think they need because it's not like your life…* (Emma)
Executing recommended practices from training	2	The team struggled to translate lessons from their pre-assessment training to real-world practice	*I think there's a formal procedure kind of like the needs assessment [module], but obviously it's kind of hard to do that in real life. Nothing ever works out as black and white as you're expecting it to...* (Emily)
Identifying appropriate needs	2	The team struggled to identify needs of the right scope that they could realistically address	*We made sure that our scope wasn't so narrow or too broad, but… it was also difficult to know what we can do because a lot of the problems were about what the government does and there were many things that we can't fix as a [student] group.* (Sophie)
Navigating language and cultural barriers	1	Language and cultural barriers impacted the team's contextual understanding during stakeholder interactions	*We were concerned that they sent their patients away because they wanted to help us, and we obviously didn't want that to be happening… That was difficult, partially a translation barrier and partially a cultural barrier. We just didn't understand what was happening.* (Jill)

Three key challenges were reported most often across participants: *Understanding the context*, *Optimizing short time in community*, and *Accessing stakeholders*.

Eleven out of twelve participants discussed challenges related to *Understanding the context* of the team's partner community. Without prior knowledge about this community, participants reported that the team struggled to plan out their data collection experiences and identify potential need areas to explore in advance. As a result, participants felt that their team's needs assessment approach was disorganized and that they could not verify the information on the community that they received from their guides:

"I felt like if we had been given slightly more information about what part of the river we were going to or had done more general research, we would've been able to target our questions more from the beginning rather than having to gather so much general information that we probably could've [learned] before." (Jill)

Jill felt that the team did not have enough information in advance to identify targeted questions to ask stakeholders. From her perspective, the team spent too much time collecting general information that could have been researched before entering the community. Several participants acknowledged that this *Understanding the context* challenge was a result of their own negligence and impacted the team's ability to plan out their observation experiences in advance as well. However, many participants also discussed that even when they tried to research the community, they had struggled to find relevant information. This challenge thus represented an outcome of the *Finding contextual information* challenge described by some participants during end of pre-assessment phase interviews.

Ten out of twelve participants cited *Optimizing short time in community* as a key challenge. These participants pointed out that they did not have time to observe the same location across multiple days or follow up with specific individuals to collect more data. As such, participants felt that they had some indication of issues in the community but were still forced to make extrapolations about specific needs based on limited data. As one participant explained:

"Even before we went, there was talk about how a needs assessment usually takes a very long time. Something I noticed during the modules was how it typically would take us months and years… because at the end of the week, I noticed that we had our needs statements, but even then from there I knew we had very little information. There was still a lot of leaping that we had to do." (John)

As John discussed, needs assessments often take months or years, compared to the single week that the team was in the community. Many participants felt that their approach was as effective as it could have been given the amount of time available; even so, John acknowledged that the team had limited information and had to rely on assumptions and extrapolations when developing needs statements. Similar to the *Understanding the context* challenge, *Optimizing short time in community* had been anticipated as a challenge by some participants during end of pre-assessment phase interviews. However, participants only elaborated on the implications of the *Optimizing short time in community* challenge for their needs assessment process after completing their data collection activities.

Seven participants described a third challenge: *Accessing stakeholders*. In addition to having limited time in the community, the team also had little control over with whom they could interact. As such, the team was not able to collect data from a fully representative sample of community stakeholder perspectives:

"We didn't always feel like we were getting a complete picture of everything, 'cause we talked to a lot of members of the community, and we didn't really get ... For example with the government, we talked to a lot of people in the community and maybe one person who's actually in the community government, and we didn't get anyone who was higher up in that spectrum, so everything was from a very one class point of view. There might be problems that they think are there, that there's a reason that they can't be solved. Or they are being worked on but they just don't really know." (Emily)

While participants wanted to collect data from a diverse group of stakeholders to develop comprehensive understandings of potential community needs, they also struggled to account for all these perspectives in practice. For example, Emily highlighted that while the team was exploring community needs related to the local government, they were largely unable to collect information related to the government's perspective on these needs. Emily felt that the team thus struggled to verify the validity of the government-related needs that they were identifying. This challenge was not anticipated by participants during end of pre-assessment phase interviews.

4.5 Discussion

4.5.1 Participant conceptions of needs assessment best practices compared to best practices in the literature

The research findings demonstrated that our participants already had some conceptions of needs assessment best practices before beginning pre-assessment activities. Participants developed these conceptions further and identified new conceptions as a result of their pre-assessment and assessment activities. Comparing participant conceptions at each stage can help us track the development of participant conceptions over time, as well as identify how the challenges encountered by participants impacted this development. The development of participant conceptions over time is summarized in Table 4.9, as well as the challenges described by participants at end of each phase.

Table 4.9 Development of participant conceptions of needs assessment best practices over time and challenges described at the end of each phase

Proportion of team	Beginning of pre-assessment phase conceptions of best practices	End of pre-assessment phase conceptions of best practices	Challenges described at end of pre-assessment phase	End of assessment phase conceptions of best practices	Challenges described at end of assessment phase
Full team (10-12 students)	Keep an open mind, Follow up with stakeholders			Account for diverse perspectives, Leverage local connections	Understanding the context, Optimizing short time in community
¾ of team (7-9 students)		Justify identified needs, Follow up with stakeholders	Overcoming team biases	Compare data across team	Accessing stakeholders
½ of team (4-6 students)	Identify potential needs in advance	Conduct research to help build rapport, Have a plan	Practicing assessment skills, Finding contextual information, Optimizing short time in community	Avoid biasing data collection, Keep an open mind about needs	Recording data during fast-paced interactions
¼ of team (0-3 students)	Don't cross boundaries, Let stakeholders guide conversation, Conduct research to understand culture, Communicate across team, Visit other places and compare data	Identify questions to ask, Be solution neutral, Avoid offending stakeholders, Identify appropriate scope of needs	Managing extensive data, Navigating language barriers	Adopt flexible data collection approach, Take good notes	Evaluating needs, Executing recommended practices from training, Identifying appropriate needs, Navigating language and cultural barriers

Comparing participant conceptions of best practices to needs assessment best practices sourced from literature (Table 4.1) can also help clarify which literature best practices participants learned during their pre-assessment and assessment phases and which literature best practices were more challenging to learn. In particular, participants developed conceptions related to identifying how their own subjectivity influenced their process, interacting with a wide variety of stakeholders, and engaging the community as equal partners. However, participants struggled to develop conceptions related to collecting many different types of data, selecting data collection methods based on specific criteria, and developing rigorous metrics to evaluate needs.

Identify how own subjectivity influences process (Darcy & Hofmann, 2003; Kretzmann & McKnight, 1993; Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Zenios et al., 2010)**.** Participants described several conceptions that related to identifying how their own subjectivity influenced their process. For instance, the suggestion *Keep an open mind* during beginning of pre-assessment phase group interviews represented a first step towards recognizing that a designer's pre-conceived notions about needs may bias the approach that the designer takes when evaluating needs (Darcy & Hofmann, 2003; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Watkins & Kavale, 2014). Several participants also acknowledged that collective group biases might influence the team's perception of community needs when discussing *Overcoming team biases* as an anticipated challenge after completing the C-SED module. Finally, participants developed an approach during their assessment activities, *Compare data across team*, that helped them manage their individual subjectivities when interpreting data and identifying community needs. However, participants did not discuss any strategies that would help them similarly account for their collective group subjectivities as part of their needs assessment process, indicating a potential knowledge gap compared to descriptions of this best practice in the literature (Darcy & Hofmann, 2003; Kretzmann & McKnight, 1993; Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Zenios et al., 2010).

Collect many different types of data (Darcy & Hofmann, 2003; Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010)**.** Conceptions related to collecting many different types of data did not emerge, likely because the team had initially expected to be collecting only observational data and thus only prepared to conduct observations. While participants described a few anecdotal examples from their assessment phase of observing objects or activities that contradicted earlier stakeholder responses, they were generally unsure how to manage these inconsistencies. Participants also encountered difficulties associated with *Recording data during fast-paced interactions* that may have impacted the team's ability to reflect on their data collection process and develop conceptions associated with this best practice.

Select data collection methods based on specific criteria (Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995)**.** A few participants described conceptions related to selecting data collection methods based on specific criteria. For instance, since participants expected to conduct observations in clinical settings, the conception *Don't cross boundaries* during beginning of pre-assessment phase group interviews represented a justification for prioritizing etic observations over emic observations or interviews with clinicians. However, this best practice was not covered in depth as part of the C-SED module. In addition, participants struggled to *Find contextual information* about the community. As participants described during end of assessment phase individual interviews when discussing the *Understanding the context* challenge, the inability to find in-depth information about the partner community in advance impacted the team's ability to plan out and justify their data collection approach. Our participants' struggles with understanding the community context thus limited opportunities for them to develop conceptions related to this best practice as part of their pre-assessment and assessment activities.

Interact with a wide variety of stakeholders (Darcy & Hofmann, 2003; Kretzmann & McKnight, 1993; Martí-Costa & Serrano-García, 1983; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010)**.** While interacting with a wide variety of stakeholders was discussed extensively as part of the C-SED module, participants did not describe conceptions related to this practice until the conception *Account for diverse perspectives* during end of assessment phase individual interviews. This conception emerged because the team encountered divergent stakeholder perspectives while collecting data in their partner community. As described in another study based on this data set (Loweth et al., 2019), the divergent stakeholder perspectives encountered by the team spurred reflective behavior in participants that translated into new conceptions related to interacting with a wide variety of stakeholders. However, while participants learned how to recognize and interpret differences in community perspectives, few participants discussed how they might reconcile divergent perspectives when defining community needs or how addressing community needs might impact various stakeholders differently. In addition, the difficulties associated with *Accessing stakeholders* and *Optimizing short time in community* restricted the variety of stakeholders that the team could interact with in practice, meaning that participants had few opportunities to develop their conceptions of this best practice further.

Develop rigorous metrics to evaluate and prioritize needs (Darcy & Hofmann, 2003; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010)**.** Participants touched on developing rigorous metrics to evaluate and prioritize needs when describing how they should *Justify identified needs*. This participant conception indicated an awareness that needs are diverse and rigorous metrics may be needed to compare needs. However, participants discussed few concrete strategies for comparing and filtering needs, which was notable given that strategies drawn from Zenios et al. (2010) and Sienko et al. (2018) for comparing and filtering needs were discussed extensively as part of the C-SED module. Participants also did not describe methods for systematically analyzing the data that they did collect, beyond *Comparing data across team* to establish shared interpretations of the team's data.

Engage community or organization as equal partners (Altschuld et al., 2014; Kretzmann & McKnight, 1993; Martí-Costa & Serrano-García, 1983; Watkins et al., 2012; Zenios et al., 2010)**.** Participants described one aspect of engaging the community or organization as equal partners when they discussed *Following up with stakeholders* during beginning and end of pre-assessment phase group interviews. As was suggested by participants, verifying needs assessment findings with the community is an important part of engaging the community as partners in the needs assessment process (Altschuld et al., 2014; Kretzmann & McKnight, 1993; Martí-Costa & Serrano-García, 1983; Watkins et al., 2012; Zenios et al., 2010). At the end of the team's assessment phase, participants also discussed the importance of *Leveraging local connections*, especially the team's guides. This second conception represented a step towards closely involving partners in needs assessment activities, another important aspect of engaging the community (Altschuld et al., 2014; Kretzmann & McKnight, 1993; Martí-Costa & Serrano-García, 1983; Watkins et al., 2012; Zenios et al., 2010). While participants did not discuss methods for building partner capabilities, this aspect of the engage community best practice was not covered as part of the C-SED module.

In summary, many participants had initial ideas related to identifying their own subjectivity and engaging the community as equal partners. Participant conceptions related to these best practices from the literature continued to develop throughout the team's pre-assessment and assessment activities, although there were a few gaps in these conceptions that future iterations of the C-SED's needs assessment module (*Socially Engaged Design Academy*, n.d.) might address. The team's assessment experiences were also instrumental in helping participants develop conceptions related to interacting with a wide variety of stakeholders.

However, participants discussed few conceptions of best practices related to collecting many types of data, selecting data collection methods based on specific criteria, or developing rigorous metrics to evaluate needs. The limited participant conceptions related to these three literature best practices may explain why several participants felt unsure about the community needs they had identified; participants felt that they did not have sufficient data after one week in the partner community and made potentially risky interpretive leaps when describing needs.

4.5.2 Assessment challenges related to cross-cultural context

The three challenges cited most frequently by participants in end of assessment phase individual interviews – *Understanding the context*, *Optimizing short time in community*, and *Accessing stakeholders* – may be characteristic of many cross-cultural projects. These challenges present unique difficulties that must be accounted for as part of a team's needs assessment process. For example, participants described difficulties finding contextual information about the partner community, particularly on the internet, that could guide the team's plans for data collection. Many cross-cultural design projects occur in small, rural and remote communities (e.g., Bryden & Johnson, 2011; Lucena et al., 2010; Aslam et al., 2014) similar to the one where our participants collected data. Logically, other project teams working in cross-cultural contexts should have encountered similar challenges with researching the partner community in advance. However, such challenges are rarely reported, perhaps because many cross-cultural project descriptions focus on the stakeholder research that was ultimately conducted rather than how the design team prepared to conduct this research. One study on how students gathered information on their stakeholders for cross-cultural projects (Garff et al. (2013)) found that their participants, like the participants in our study, did not leverage online resources much to gather information about stakeholders because there was little relevant information available. Instead, the participants in Garff et al. (2013) were more likely to seek information directly from local partners. While local partners can be a great source of otherwise difficult-to-find information during the pre-assessment phase (Watkins et al., 2012), participants in our study did not think to ask their guides for more contextual information about the community until after they were already in the partner community.

While local partner involvement in pre-assessment contextual research is ideal, close communication with local partners may not always be possible. In such cases, there are several other potential sources that designers might leverage to conduct contextual research. For instance, designers might research needs that are experienced in similar communities (Witkin & Altschuld, 1995) and previous solutions to these needs (Lucena et al., 2010; Zenios et al., 2010). This type of contextual research can help designers develop standards of comparison that may help them identify unique needs once they enter the partner community. In addition, research into other previous needs assessments might help designers think about relevant types of data to collect (Lucena et al., 2010; Watkins et al., 2012; Witkin & Altschuld, 1995), or identify how their implicit conceptual models might be influencing their initial ideas about community needs (Darcy & Hofmann, 2003; Leydens & Lucena, 2014; Lucena et al., 2010). This type of research could have helped participants in this study be more intentional in selecting their data collection methods during their pre-assessment phase. Finally, designers might look for macro-level information, such as census data or information about available services, that could facilitate identification of preliminary needs (Royse et al., 2009; Stevenson & Mattson, 2019). This information could help establish a baseline for what designers should expect to see in the community, which may lead to surprising insights during assessment activities if the census or services information does not match reality.

In addition, the time and access challenges encountered by participants in this study are not uncommon for cross-cultural design projects but may point to a tension that is unique to needs assessment activities. For instance, full needs assessments typically occur over months or years (Kretzmann & McKnight, 1993; Royse et al., 2009; Watkins et al., 2012; Witkin & Altschuld, 1995), although some sources (e.g., Darcy & Hoffman, 2003) discuss a more rapid approach for quickly prioritizing necessary knowledge in crisis situations. A long time frame allows the needs assessment team to collect enough data and interact with enough stakeholders to develop comprehensive descriptions of community needs. However, one to two-week data collection experiences are common for cross-cultural design projects involving students due to the restrictive realities of cost, distance and student schedules (e.g., Gutierrez Soto & Dzwonczyk, 2015; Simon et al., 2012; Tendick-Matesanz et al., 2015; Viswanathan & Sridharan, 2012). From one perspective, these short experiences can lead to substantial learning gains for students, similar to the gains observed in this study (Gutierrez Soto & Dzwonczyk, 2015; Simon et al., 2012; Viswanathan & Sridharan, 2012). However, there remains a question as to whether valid community needs can be identified in only a week or two (Lucena et al., 2010; Witkin & Altschuld, 1995; Zenios et al., 2010).

Faced with challenges related to time and access, recommendations include relying on local partners to collect additional information (Simon et al., 2012; Tendick-Matesanz et al., 2015) or having a team representative stay in the community for several months as a semi-permanent liaison (Bargar et al., 2016). However, students may struggle to acquire timely or accurate information from local partners because these partners often have their own important responsibilities in the community (Gutierrez Soto & Dzwonczyk, 2015). As such, while continued contact with local partners is certainly important, engineering students would also benefit from pedagogical structures that could help them both navigate limitations related to time or access to stakeholders in the community and also set project goals that properly account for these limitations.

4.5.3 Limitations

One potential study limitation was the unique composition of the needs assessment team. The team represented a diverse collection of different engineering disciplines, and many participants were also pursuing non-engineering double majors or minors. The diversity of disciplinary perspectives available to the team may have helped participants develop conceptions of best practices related to recognizing their own subjectivity that perhaps would not have emerged on a team with less disciplinary diversity (Lucena et al., 2010). On the other hand, the team exhibited little gender diversity with eleven out of twelve participants identifying as female. It is unclear how our findings would change in the context of a team with more gender diversity, or in the context of a team composed primarily of men.

Another study limitation was that we did not directly track the activities of the team while they were collecting data in the community. As such, we are unable to verify how participant descriptions of needs assessment activities corresponded to what the team did in practice.

A third limitation was that the end of assessment phase interviews completed with each participant occurred right after the team returned from collecting data in the partner community. At this point, assessment experiences were still salient and participants could easily describe what they had learned. It is unclear which learning gains from the needs assessment experience have continued to be salient over time, especially since participants did not have consistent additional opportunities after this experience to practice what they had learned (Kolb, 1984).

4.5.4 Implications for design pedagogy and practice

One implication of this study is that design educators can use the needs assessment framework (including general process and best practices) described in Sections 4.2.1 and 4.2.2 to develop pedagogy for student teams that are performing needs assessments. While the main focus of our study was on needs assessments in cross-cultural contexts, the framework presented in this paper is likely transferrable to situations where engineering students are conducting needs assessments within cultures more similar to their own (Royse et al., 2009; Witkin & Altschuld, 1995; Zenios et al., 2010). For example, Lima (2013) demonstrated how identifying the ways that a designer's subjectivity influences their process, interacting with a wide variety of stakeholders, and engaging the community as equal partners helped engineering students identify and evaluate needs as part of local community-based design projects. Furthermore, the in-depth case example presented in our findings and discussion highlighted which needs assessment best practices some engineering students might already have an intuitive understanding of, such as engaging the community, and which best practices some engineering students may struggle with, such as developing rigorous metrics to evaluate needs.

The study findings also suggest that engineering students need support when specifying goals for their needs assessments. Effective teams specify clear goals at the outset of the needs assessment; these goals help the team identify key stakeholders and develop their data collection plan (Darcy & Hofmann, 2003; Kretzmann & McKnight, 1993; Royse et al., 2009; Sleezer et al., 2014; Watkins et al., 2012; Witkin & Altschuld, 1995; Zenios et al., 2010). Specifying clear goals is vital for cross-cultural needs assessments because clear goals can help designers navigate challenges related to finding contextual information and time or access constraints. Meanwhile, teams that are less explicit about their goals may struggle to identify community needs that can reasonably be addressed and may unintentionally mislead partner communities or organizations about the timeline of potential solutions. While the specific contexts of cross-cultural student projects may differ, the challenges experienced by the team in this study are likely transferrable (Darcy & Hofmann, 2003; Watkins et al., 2012; Witkin & Altschuld, 1995). As such, other design teams and educators could use this case to help them specify appropriate needs assessment goals given constraints on time, access, and available contextual information.

Finally, our findings suggest that engineering students that are interested in conducting needs assessments for cross-cultural design projects may need more curricular instruction in applying qualitative data collection methods and analyzing qualitative findings. Certain design questions, especially those related to identifying stakeholder needs, are best addressed through qualitative research and analysis. However, participant challenges with collecting many types of data, selecting data collection methods to use, and developing rigorous metrics to evaluate needs point to a gap in student knowledge related to applying qualitative methods and analyzing findings. Previous studies have reported similar gaps in student knowledge, for instance in the context of capstone courses (Mohedas et al., 2014a, 2014b). However, in the context of this study, participant knowledge gaps related to collecting and analyzing qualitative data directly impacted participants' abilities to assess community needs properly.

4.6 Conclusion

This study followed an undergraduate engineering team as they conducted a needs assessment to understand what these students already knew about needs assessments, how they conducted a needs assessment in practice, and their learning gains from experience conducting a needs assessment. Participants expanded their understandings of best practices related to identifying their own subjectivity, engaging the community as equal partners, and interacting with a variety of stakeholders. However, participants did not describe many conceptions related to collecting several different types of data, selecting data collection methods based on specific criteria, or developing metrics to evaluate needs. As a result, participants felt that their assessment phase was successful but at the same time were unsure whether they had collected enough data to identify community needs effectively and did not know how best to select a need to address going forward. These findings suggest that engineering students engaged in cross-cultural design projects would benefit from additional pedagogical support for specifying project goals, collecting qualitative data related to these goals, and analyzing these data. Best practices for needs assessments synthesized from the literature and described in this paper, as well as our descriptions of student challenges, can support the shaping of this pedagogy to help engineering students develop skills to apply when working on cross-cultural design projects.

4.7 References

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Chapter 5 An In-Depth Investigation of Student Information Gathering Meetings with Stakeholders and Domain Experts[11]

5.1 Introduction

Information gathering activities play an important role in engineering design projects. These projects often start out with "ill-defined" problems, and designers rarely begin with all of the necessary information they need to develop effective solutions (Buchanan, 1992; Goel & Pirolli, 1992). For instance, designers often must gather additional information to develop a more comprehensive understanding of the stakeholder needs that may be driving their design problem (Coleman et al., 2016; Zenios et al., 2010). Moreover, designers may need to gather additional information to identify the full range of stakeholder requirements that must be met for a solution to be successful (Bursic & Atman, 1997; Dieter & Schmidt, 2013; Sutcliffe & Sawyer, 2013). There are many other types of information that designers may also want to gather depending on the stage of their design project; in each case, this additional information can help designers make effective design decisions as they develop their solution concepts.

One way that designers can gather additional information about their design problem is by conducting information gathering meetings with project stakeholders or domain experts (IDEO, 2015; Rosenthal & Capper, 2006; Wooten & Rowley, 1995). However, previous studies of student designers suggest that they may struggle to conduct effective information gathering

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meetings, for instance due to difficulties formulating effective interview questions or adopting stakeholder language (Bano et al., 2019; Luck, 2007; Mohedas et al., 2014). These challenges with gathering information may negatively affect student designers' abilities to identify relevant stakeholder requirements and/or deliver solutions that address stakeholder needs (Bursic & Atman, 1997; Loweth et al., 2019; Mohedas et al., 2015). While several studies have explored how information gathering meetings, particularly with stakeholders, may impact student design processes (Hess & Fila, 2016; Mohedas et al., 2015; van Rijn et al., 2011), few studies thus far have provided detailed descriptions of the different ways that students in capstone contexts may attempt to gather information as part of their information gathering meetings. To address this research gap, our study analyzed recordings of information gathering meetings that student capstone design teams conducted with project stakeholders and domain experts to understand how students gathered information as part of their projects. The in-depth descriptions presented in our study highlight approaches to gathering information that students may already be implementing effectively, as well as gaps in their approaches that future pedagogy may address.

5.2 Background

5.2.1 Recommended practices for gathering information

There are several practices that designers may employ to gather information effectively from stakeholders or domain experts. For example, designers may conduct "deep dive" interviews that explore stakeholder or domain expert knowledge or experiences (IDEO, 2015; Kouprie & Sleeswijk Visser, 2009; Wooten & Rowley, 1995). A key feature of these "deep dive" interviews is the use of open-ended questions that, rather than confirming the designer's prior notions about stakeholder needs and requirements, elicit stories and invite the interviewee to provide surprising information (IDEO, 2015; Kouprie & Sleeswijk Visser, 2009; Rosenthal & Capper, 2006).

Designers may also employ practices that help stakeholders or domain experts communicate their ideas. For instance, the use of prototypes or other visual representations as “boundary objects” can provide individuals with an additional non-verbal means of expressing themselves that may reduce ambiguity (Deininger et al., 2017; Ewenstein & Whyte, 2009; Stappers et al., 2009). In addition, including stakeholders as design team participants can in some cases enable stakeholders to communicate their own design ideas using the designer’s language (Luck, 2018; Østergaard et al., 2018).

Furthermore, designers may strive to develop a mutual language with stakeholders or domain experts that is mutually comprehensible despite different backgrounds or experiences (Bucciarelli, 2002; Kleinsmann et al., 2007). This mutual language may enable designers and stakeholders or domain experts to engage in “co-inquiry” where they combine their respective disciplinary knowledge to generate new, equally-accessible knowledge about the design problem (Adams et al., 2018; Lehoux et al., 2011). Together, participatory techniques and development of a mutual language can help stakeholders and domain experts contribute relevant project information that may not have been explicitly requested by the designers as part of a planned protocol (Adams et al., 2018; Luck, 2018).

5.2.2 Student designer approaches to gathering information

While there are several practices that designers may employ to gather information from stakeholders or domain experts, it is unclear how and to what extent student designers are employing these practices as part of their curricular design experiences. Previous studies have mainly discussed whether conducting information gathering meetings with stakeholders helped student designers identify relevant stakeholder requirements and/or develop solution concepts that addressed stakeholder needs (Hess & Fila, 2016; Mohedas et al., 2015; van Rijn et al., 2011). However, these studies did not specify if meetings with stakeholders were helpful because students leveraged effective information gathering practices or despite students employing ineffective ones. This distinction is important because other studies (Bano et al., 2019; Luck, 2007; Mohedas et al., 2014) have highlighted student challenges with gathering information from stakeholders but did not describe how often these challenges occurred over time or what the consequences of these challenges might have been for the information that students gathered.

This knowledge gap may exist because many previous studies of student information gathering activities have focused on student designers' approaches as a whole over the course of their curricular design projects (Coleman et al., 2016; Lai et al., 2010; Mohedas et al., 2014). For example, Mohedas et al. (2014) interviewed capstone design teams about their experiences gathering information from stakeholders but did not collect data on the content of student meetings to compare with student perceptions of their meetings. By comparison, Hess and Fila (2016) and Modehas et al. (2015) both collected data on student meetings with stakeholders; however, these two studies mainly examined how information gathering meetings influenced student decisions related to stakeholder requirements and/or solution concepts and did not describe the content of these meetings in depth. One study that did provide detailed examples of student information gathering meeting behaviors was Luck's (2007) description of a recently-graduated architecture student's interactions with stakeholders in a focus group setting. However, this example is limited to a specific design context that may not necessarily translate to other types of design projects. In addition, recent work by Mohedas et al. (2016) and by Bano et al. (2019) has documented how student designers gather information from stakeholders in controlled settings involving research-based, simulated design tasks. However, more data is needed to understand how student designers gather information in curricular design contexts, such as capstone projects, and how student information gathering approaches may impact their design processes.

5.3 Research design

5.3.1 Research questions

The goal of our study was to describe the information gathering behaviors that capstone design students exhibited during their information gathering meetings with project stakeholders and domain experts. Our study was guided by the following research questions:

1. What types of information gathering behaviors do student designers exhibit in meetings with stakeholders and domain experts? What are the characteristics of these behaviors?
2. In what ways are these information gathering behaviors similar to recommended best practices for gathering information?

We used a qualitative research approach to explore the different ways that students gathered information related to their capstone projects during their meetings with stakeholders and domain experts. Qualitative research methods are ideal for developing deep contextual understandings of human interactions (Borrego et al., 2009; Creswell & Plano Clark, 2018; Leydens et al., 2004; Maxwell, 2013) and are commonly used for this purpose in design research (Adams et al., 2018; Luck, 2007; Stempfle & Badke-Schaub, 2002). The methods we employed in this study facilitated our identification of specific information gathering behaviors that students exhibited during their meetings, as well as the relevant details that defined these behaviors.

5.3.2 Context and participants

The context of our study was a single-semester senior-level capstone design course at a large Midwestern university. This capstone course spanned several different design stages including problem definition, concept generation and selection, design iteration and prototyping, and verification and validation, thus allowing us to observe student information gathering behaviors across multiple different project stages. Participants included 24 students from six student design teams enrolled in the capstone course, which is an appropriate sample of teams given the in-depth research methods leveraged and is larger than other similar studies of design team communication and information gathering involving one to three teams (Safin et al., 2021; Stappers et al., 2009; Stempfle & Badke-Schaub, 2002). Participants worked in teams of three to five undergraduate students majoring in mechanical engineering, with each team developing a prototype to address a different and unique design problem. While all participants had completed the required mechanical design course sequence, some participants also discussed exposure to other design experiences such as internships, co-curricular projects, and design electives. For all but one of the participants, their capstone design course represented their first experience conducting information gathering meetings, particularly with stakeholders, to inform their design projects. Both the composition of the six teams and their project foci are included in Table 5.1.

Table 5.1 Capstone team project focus and composition

Team	Type of project	Sex of team members	Race/Ethnicity of team members
A	Developing assistive device	1 Female, 2 Male	1 Asian, 1 Hispanic, 1 White
B	Developing assistive device	1 Female, 4 Male	3 Asian, 2 White
C	Developing assistive device	1 Female, 4 Male	2 Asian, 3 White
D	Modifying university space	1 Female, 3 Male	4 White
E	Developing measurement tool	3 Male	3 White
F	Modifying university space	4 Male	4 White

5.3.3 Data collection

Participants were initially invited to participate in our study as part of a project-selection survey during the first week of the semester. After the capstone instructor assigned teams to projects, we sent formal invitation emails to teams that had expressed interest in participating.

We collected several different types of data from participants, including 1) recordings of information gathering meetings, 2) semi-structured researcher interviews with participants, 3) participant notes from stakeholder/domain expert meetings, and 4) agendas that participants used to prepare for their meetings. The goal of data collection was to develop rich descriptions of student information gathering behaviors that could facilitate comparison of these behaviors across teams and that could enable us to identify aspects of these behaviors that may be transferrable to other design contexts (Borrego et al., 2009; Leydens et al., 2004).

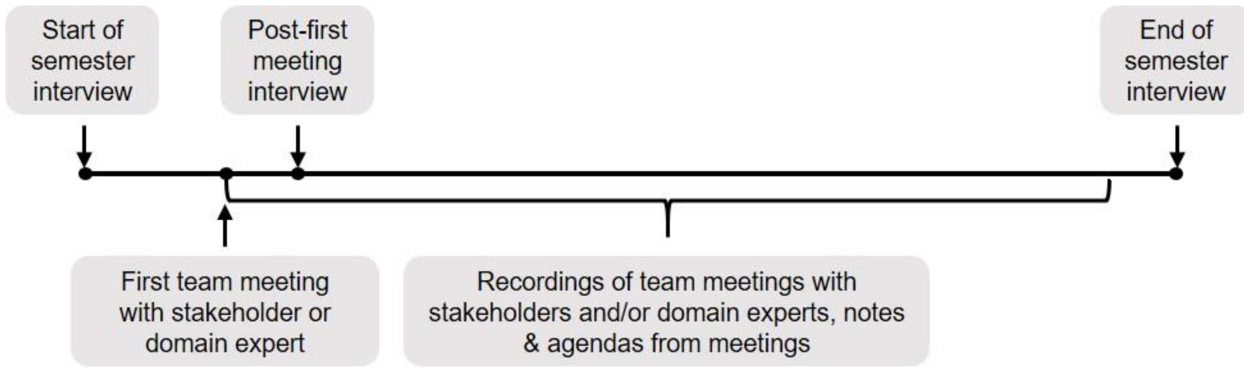
Recordings of Information Gathering Meetings. All teams were asked to submit recordings of information gathering "interviews" that they conducted with stakeholders or domain experts over the semester, as well as interview agendas, protocols, or notes. We originally used the term "interview" in our instructions to participants, although we elaborated that these "interviews" included all types of information gathering engagements that teams conducted as part of their projects. During semi-structured researcher interviews, we found that participants consistently preferred the term "meeting" over "interview" in describing their information gathering engagements with stakeholders or domain experts. We thus adopted our participants' terminology in referring to these engagements as "information gathering meetings."

Participants obtained verbal consent from stakeholders and domain experts before recording and clarified that no personally identifiable information from these individuals would appear in our study. Each participant was compensated $10 per recording submitted by their team, with a maximum possible compensation of $100. We initially recruited eight teams to participate in our study, but two teams had non-disclosure agreements with their primary stakeholders and thus were unable to submit recordings. The remaining six teams submitted recordings of 19 meetings representing over 14 hours of audio data. Fourteen of these meetings involved just stakeholders, four meetings involved just domain experts (typically university professors or outside consultants), and one meeting involved both stakeholders and domain experts.

Semi-Structured Researcher Interviews. Teams were also asked to complete three semi-structured interviews with a member of our research team. In keeping with rigorous qualitative methodology, we used these interviews to verify that our interpretations of the information gathering meetings submitted by participants aligned with participant interpretations of their meetings (Borrego et al., 2009; Creswell & Plano Clark, 2018; Leydens et al., 2004; Maxwell, 2013). Participants were compensated $25 per interview.

Figure 5.1 depicts the timing of the three researcher interviews. The first interview occurred before teams conducted their first information gathering meeting and sought to understand the background and previous design experiences of each participant. The second interview occurred a week after teams conducted their first information gathering meeting and explored team perceptions of this meeting. The third interview occurred at the end of the semester; during this interview, teams reflected on their meeting experiences holistically.

Figure 5.1 Data collection timeline

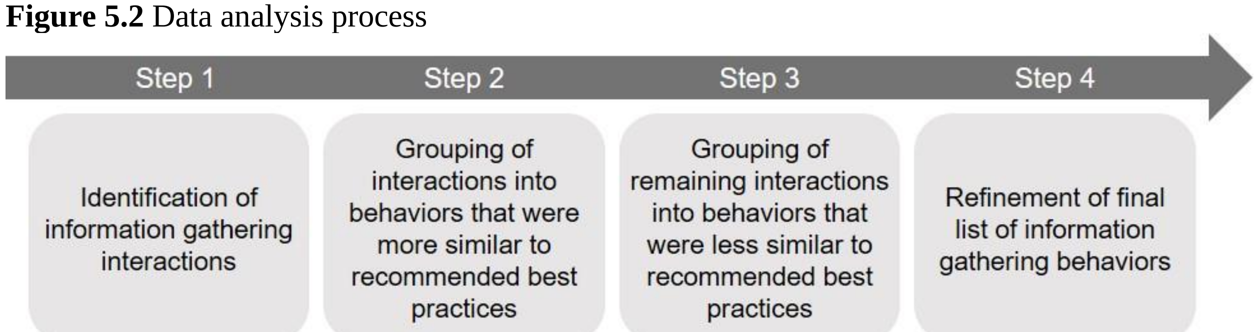


Interview protocols were developed for each interview to ensure comparability across participant responses (Leydens et al., 2004; Maxwell, 2013). Protocols were organized around open-ended questions designed to elicit stories and examples from participants while also allowing the interviewer space to opportunistically probe responses for greater depth. We also piloted each protocol with undergraduate students who had previously worked on similar design projects; these pilot interviews in turn informed further iterations on our interview questions. In total, our study collected 20 hours of audio data from interviews to supplement the 14 hours of audio data collected from stakeholder meetings.

5.3.4 Data analysis

Our data analysis proceeded through four steps, as outlined in Figure 5.2. These steps are described in greater detail in the following sub-sections.

Figure 5.2 Data analysis process



Step 1. All recordings of student information gathering meetings and researcher interviews were transcribed and checked for accuracy by two members of our research team. Transcripts of student information gathering meetings were then inductively coded by these two researchers to identify and define specific ways that students interacted with stakeholders or domain experts when gathering information during meetings. In this context, inductive coding involved reading through meeting transcripts, highlighting unique interactions where students gathered information, and defining these interactions descriptively rather than according to a pre-defined set of codes (Creswell & Plano Clark, 2018; Miles et al., 2014; Patton, 2015). Each identified interaction consisted of a series of questions asked or statements made by the student team as they gathered information. Our initial round of analysis resulted in an inventory of information gathering interactions identified across the six teams and was completed using NVivo 12, a qualitative coding software. An example selection of initial identified interaction codes is shown in Table 5.2.

Table 5.2 Examples of identified information gathering interactions from student information gathering meetings

Identified interaction	Definition of interaction	Example
Repeat response	Students paraphrase stakeholder's or domain expert's earlier response when asking a clarification question	*"So to discuss the sources of [the issue], you said it's mostly [this source], and of course it sounds like there's a lot of interactions [contributing to that source]."*
Validate contribution	Students validate stakeholder's or domain expert's contribution to the meeting	*"[Your] questions are really helpful. There are things we may not have thought of."*
Ask closed-ended question	Students ask a closed-ended question when transitioning to a new discussion topic	*"Okay, and is there any similar device that exists that tries to serve that same purpose, or is it a pretty un-tackled problem right now trying to really quantify [this metric]?"*

Step 2. We next grouped together similar identified interactions and defined these groupings as distinct information gathering behaviors. These information gathering behaviors

captured the overarching ways that teams in our study gathered information during their meetings. We based our initial list of information gathering behaviors on a list of interview best practices developed by Mohedas (2016)/Mohedas et al. (2016) to facilitate comparison between the behaviors that teams exhibited in their meetings and recommended best practices for information gathering from the literature. An example of our initial grouping process based on the list from Mohedas (2016)/Mohedas et al. (2016) is shown in Table 5.3.

Table 5.3 Example of grouping identified interactions into information gathering behaviors

Information gathering behavior	Definition of behavior	Identified interactions that were grouped into behavior	Definition of interaction	Example
Avoid Misinterpretations [from Mohedas (2016)/Mohedas et al. (2016)]	**Students repeat and clarify stakeholder's or domain expert's responses to make sure that accurate information is being collected**	Repeat response	Students paraphrase stakeholder/domain expert's earlier response when asking a clarification question	*"So to discuss the sources of [the issue], you said it's mostly [this source], and of course it sounds like there's a lot of interactions [contributing to that source]."*
		Check interpretation	Students double check that they made a correct inference from stakeholder's description	*"And what kind of tables? Are they circular tables or are they long tables?"*

We encountered two issues during this initial grouping process. First, the list of best practices described in Mohedas (2016)/Mohedas et al. (2016) was compiled primarily from literature sources (e.g., Rosenthal and Capper, 2006; Wooten and Rowley, 1995) with a specific focus on informational interviews for identifying stakeholder needs and/or requirements. However, informational interviews are not the only context during which designers might gather information from stakeholders or domain experts; as noted in our "Data Collection" section, "meeting" was the preferred term that many of the participants in our study used when discussing their engagements. Thus, as we grouped our identified interactions, we revised and expanded our initial list of information gathering behaviors to account for additional practices related to exploring stakeholder experiences in depth in meeting or co-design contexts (Coleman et al., 2016; IDEO, 2015), employing prototypes to gather information (Deininger et al., 2017; Ewenstein & Whyte, 2009; Stappers et al., 2009), and developing a mutual language with stakeholders or domain experts to improve communication (Adams et al., 2018; Bucciarelli, 2002; Kleinsmann et al., 2007).

The second issues that we encountered while grouping identified interactions into distinct information gathering behaviors was that many identified interactions resembled recommended best practices, but few matched the literature descriptions of these best practices exactly. We also observed noticeable variety in how teams exhibited certain types of interactions. For instance, one of our identified interaction codes was "ask open-ended questions" to invite deep responses from stakeholders. However, the depth of response that may be elicited from open-ended questions may vary substantially depending on the question. To use two examples from our data, "*Could you tell us a little bit about how we might interface with [this stakeholder], and what we could go back and forth with them about?*" is an open-ended question that is soliciting details on how to contact an individual as well as a suggested list of discussion topics. By comparison, "*How do we verify that doing something like that with a [prototype] here is scalable, for example?*" is soliciting a process and also asking, in this case a domain expert, to think more critically about the design problem and what it may mean from their experience to "verify" a prototype. To account for the observed variation in how teams exhibited each behavior in our data, we thus titled our list of behaviors that resembled information gathering best practices as *behaviors that were more similar to recommended best practices*.

We ultimately grouped identified interactions into 11 information gathering behaviors that were more similar to recommended best practices. We also classified these 11 behaviors into *structural*, *exploratory*, and *collaborative* categories based upon similarities that we saw across the behaviors. These similarities were based upon the types of information that each behavior seemed to elicit during meetings as well as the types of meeting situations where students exhibited each behavior. Our categorization is described in greater depth in our "Findings" section.

Step 3. Our 11 information gathering behaviors that were more similar to recommended best practices did not capture all identified interactions from our initial round of coding. Our remaining identified interactions all diverged from recommended practices in specific ways. As a result, we grouped remaining identified interactions into 11 additional behaviors that we categorized as *behaviors that were less similar to recommended best practices* since each behavior in this category contrasted strongly with one of our behaviors that was more similar to recommended best practices. For example, the behavior *elicit shallow responses* (shown in Table 5.4) encompassed several remaining identified interactions that all principally diverged from the behavior *encourage deep thinking*. This second grouping process accounted for all remaining identified interactions from our initial round of coding.

Table 5.4 Example of grouping remaining identified interactions into information gathering behaviors that were less similar to recommended best practices

Information gathering behavior that was less similar to recommended best practices	Definition of behavior	Remaining identified interactions that were grouped into behavior	Definition of interaction	Example
Elicit Shallow Responses	**Students ask questions that implicitly constrain stakeholder**	Ask a closed-ended question	Students ask a closed-ended question when transitioning to a new discussion topic	*"Okay, and is there any similar device that exists that tries to serve that same purpose, or is it a pretty un-tackled problem right now?"*

or domain expert responses	Ask multiple questions	Students ask multiple questions at once without first giving the stakeholder or domain expert the opportunity to answer	*"What it's like to go in the [space] for a [stakeholder]? Can you tell us what that's like? Do they bring their own [materials]?"*

Step 4. Lastly, the two original coders reviewed the meeting transcripts again to identify any information gathering interactions that had been missed during the initial round of inductive coding and that aligned with one of the 22 information gathering behaviors from our final list. After this second transcript review, we discussed remaining interactions that did not cleanly align with one of the defined behaviors, as well as interactions that had been grouped differently by the two researchers. Discussing these discrepancies helped us clarify and iterate on our definitions of the 22 information gathering behaviors observed in this study; these definitions were further validated through comparison to participant descriptions obtained through researcher interviews of how teams gathered information during their meetings.

5.4 Findings

Table 5.5 shows the full list of 22 information gathering behaviors that student teams exhibited in their meetings with stakeholders and domain experts. Since student *structural* information gathering behaviors mainly involved practices for meeting organization and basic clarification rather than in-depth information gathering, we only describe student *exploratory* and *collaborative* behaviors in depth in the following sub-sections.

Table 5.5 List of behaviors that students exhibited during their information gathering meetings with stakeholders and domain experts

	More similar to recommended best practices		Less similar to recommended best practices	
	Behavior	Definition	Behavior	Definition
Structural Behaviors	**Build Rapport with the Stakeholder or Domain Expert**	Students express their appreciation of the stakeholder's or domain expert's contributions and seek to help the individual feel comfortable during the meeting	**Damage Rapport**	Students express judgment of the stakeholder's or domain expert's contributions or otherwise cause the stakeholder or domain expert to feel uncomfortable during the meeting
	Avoid Misinterpretations	Students repeat and clarify the stakeholder's or domain expert's responses to make sure that accurate information is being collected	**Muddle Information Received from the Stakeholder or Domain Expert**	Students use imprecise language and/or allow technical difficulties to decrease the clarity of the stakeholder's or domain expert's responses and thus insert ambiguities into collected information
	Guide Meeting Direction while Inviting Stakeholder or Domain Expert Input	Students clarify the purpose of the meeting and consistently guide the meeting direction while also inviting the stakeholder or domain expert to suggest topics of interest	**Cede Guidance of Meeting**	Students surrender to the stakeholder or domain expert the position of guiding the meeting direction and/or exhibit uncertainty as to who should be guiding the meeting at a given moment
Exploratory Behaviors	**Encourage Deep Thinking**	Students ask questions that encourage the stakeholder or domain expert to move beyond superficial responses and provide detailed knowledge on a given subject	**Elicit Shallow Responses**	Students ask questions that implicitly constrain stakeholder or domain expert responses
	Flexibly & Opportunistically Probe Responses	Students employ spontaneous probes, as indicated by vocal cues indicating surprise or curiosity, to dive deeper into the stakeholder's or domain expert's experiences or knowledge	**Rigidly Adhere to Structure**	Students resist departing from the pre-determined topics of the meeting
	Verify the Conclusions Drawn from Meetings	Students check that their conclusions drawn from the meeting match with the stakeholder's or domain expert's own perceptions	**Lead the Stakeholder or Domain Expert to Conclusion**	Students indicate a suggested or preferred answer when asking questions or soliciting feedback and thus influence the stakeholder's or domain expert's response
	Delve into Stakeholder or Domain Expert Experiences	Students evoke specific ideas or experiences of the stakeholder or domain expert to better understand how the individual thinks and feels about the design problem	**Conflate Student and Stakeholder or Domain Expert Experiences**	Students suggest that the stakeholder or domain expert's experiences likely resemble their own and do not explore the individual's experiences in greater depth

	Use a Co-Creative Meeting Strategy	Students establish space within the meeting for the stakeholder or domain expert to make project decisions or give design feedback	**Use a Student-Centered Meeting Strategy**	Students control the goals of the meeting and project, making decisions and informing the stakeholder or domain expert of those decisions rather than soliciting input on those decisions
Collaborative Behaviors	**Develop Mutual Understanding with the Stakeholder or Domain Expert**	Students leverage language and/or design representations that help them to communicate across disciplinary barriers and develop mutual understanding about the design project	**Assume Stakeholder's or Domain Expert's Understanding**	Students embed assumptions about the stakeholder's or domain expert's understanding of the design project in their questions or language
	Introduce Relevant Information	Students provide relevant knowledge about the design project to build a repository of shared information between the design team and the stakeholder or domain expert	**Introduce Unclear Information**	Students provide information about the design project but do not clearly explain the meaning of the information and/or clarify that the information is likely inaccurate
	Explore Differences Between Perspectives	Students explore the nuances of the stakeholder's or domain expert's point of view by presenting the differing perspective of another stakeholder or domain expert not present at the meeting	**Place Own Perspective Above Others'**	Students describe the perspectives of other stakeholders or domain experts not present at the meeting but dismiss these other perspectives as irrelevant to the project

5.4.1 Exploratory information gathering behaviors

Exploratory information gathering behaviors represented ways that students tried to obtain deeper insights about stakeholder or domain expert perspectives and experiences. *Exploratory* behaviors that were more similar to recommended best practices (*encourage deep thinking*, *flexibly & opportunistically probe responses*, *verify the conclusions drawn from meetings*, and *delve into stakeholder or domain expert experiences*) helped students explore the responses of others in greater depth to uncover new and surprising insights about their design problem. By comparison, *exploratory* behaviors that were less similar to recommended best practices (*elicit shallow responses*, *rigidly adhere to structure*, *lead the stakeholder or domain expert to conclusion*, and *conflate student and stakeholder or domain expert experiences*) constrained the range and potential depth of stakeholder or domain expert responses.

The following example of the *delve into stakeholder or domain expert experiences* behavior demonstrates how *exploratory* behaviors that were more similar to recommended best practices helped students explore stakeholder or domain expert perspectives and uncover new aspects of their design problem. This example comes from a meeting conducted by Team E, who was working with their primary stakeholders to develop a safety measurement tool. In this case, Team E was meeting with an engineer who had built a previous iteration of the tool to learn more about how the current design might be improved:

Team E: *So you're speaking to the subcommittee [who sets measurement standards]… **If there were to be a time when a [measurement] standard was put into there, what would go into that process?***

Engineer: *Well first we have to say, "Okay there's a possibility of injury," either real or perception… We discuss if there's a need for a [measurement] standard for the [product] to prevent [injury]. Then we do studies to see what the issue is and how we can prevent it, what kind of tests we need to do to ensure that does not happen.*

Team E: *Sure. So if you determined that a specific [deformation] was dangerous, would the subcommittee also recommend a specific device and method for [measurement] as*

Engineer: *part of those standards?*

…If there is [data] and a method to saying, okay, the [product deformation] caused that injury, and then there's a method that you guys perform and suggest, the subcommittee will take that over and do the testing and validate that what you guys have come up with is correct. And they'll go through the motion of getting that approved and adding that to the [measurement] standard.

Team E's initial open-ended question invited the engineer to speak about their experience with implementing a measurement standard. Team E also probed the engineer's response to learn more about how this measurement standard might relate to the tool they were developing. This exploration by Team E thus led to the discovery of important new contextual information about how their measurement tool might be used in practice.

Conversely, the following example demonstrates how *exploratory* behaviors that were less similar to recommended best practices constrained the range of potential stakeholder or domain expert responses. This excerpt, featuring Team A, represents both the *elicit shallow responses* and the *conflate student and stakeholder or domain expert experiences* behaviors. Team A was working on an assistive device for a young person with a disability. Their primary point of contact was a volunteer who worked for the non-profit that was funding Team A's project and who knew the team's user personally. In this exchange, Team A was meeting with the volunteer for the first time and was trying to clarify their user requirements:

Team A: ***What is [the user's] age, 'cause I know if you want it to be adjustable I imagine if she is between 12 and 14 she will probably continue to grow.***

Volunteer: *So right now she's 16 or 17 but our goal is for it to be adjustable for future [users] too. I mean, all of our kids are under 19. Generally if they have a diagnosis that they need to use [this device] they're generally smaller 'cause generally they're kids who are in wheelchairs… who aren't overweight necessarily or large.*

Team A: ***This might be a weird number to ask but do you know on average do they get to be super tall kids or not really? So we can know how much…***

Volunteer: *It just kind of depends, generally if the kid's over, I'm trying to think 'cause I'm… so generally, it's hard to gauge 'cause they're not standing, I'd have to look and see how tall [the user] is but she'd probably be my height if she were standing and if they're much taller than [that], we probably wouldn't utilize the [device]… does that make sense?*

Team A: ***That answers my question perfectly… We can test this on me ...***

Team A was looking for two specific pieces of information, the user's age and height, that they needed to develop their user requirements. However, Team A worded their questions in a way that suggested that they already knew this information (i.e., *elicited shallow responses*). Rather than providing an open response that might have led to surprising insights for the team, the volunteer instead commented on Team A's perspective and provided minor additional details that did not significantly challenge Team A's prior conceptions about their user or push the team to think more deeply about how their user's experience may differ from their own. As a result, Team A concluded that they could test the prototype on one of their team members rather than involving their user (i.e., *conflated student and stakeholder or domain expert experiences*). It is thus unclear if Team A's eventual solution accounted for their user's unique capabilities or preferences.

5.4.2 Collaborative information gathering behaviors

Collaborative information gathering behaviors represented ways that students tried to facilitate the participation of stakeholders or domain experts during information gathering meetings. *Collaborative* behaviors that were more similar to recommended best practices (*use a co-creative meeting strategy*, *develop mutual understanding with the stakeholder or domain expert, introduce relevant knowledge,* and *explore differences between perspectives*) bridged differences in understanding between students and stakeholders or domain experts that resulted from differences in domain background, past experiences, or knowledge about the team's design problem. These behaviors also helped stakeholders and domain experts contribute relevant information without explicit prompting from the student team. In contrast, *collaborative* behaviors that were less similar to recommended best practices (*use a student-centered meeting strategy*, *assume stakeholder's or domain expert's understanding*, *introduce unclear information*, and *place own perspective above others'*) made it more difficult for stakeholders or domain experts to discern what information might be most relevant to provide to the design team and/or articulate their own understanding of the design project.

The following example of the *develop mutual understanding with the stakeholder or domain expert* behavior demonstrates how *collaborative* behaviors that were more similar to recommended best practices helped students solicit more informed responses from stakeholders or domain experts. This excerpt comes from a meeting conducted by Team C, who was building an assistive device for a young person with a disability ("the user"). During this meeting, Team C wanted to solicit design feedback from both their user and their user's caregivers. Team C thus opened this meeting with:

Team C: *Since we last met with you…* ***We've put together a couple of our preliminary ideas… put together the design requirements from the feedback you gave us. Based on that, we built a couple of [functional] prototypes we brought to show you today… they're the rough sketch of what we're thinking. We want to get your feedback on them, and then we're going to take one of those… and try to build that full-scale… [The] final design will be a lot more fleshed out, but***

… ***these [prototypes] illustrate the design ideas we're looking at.***

Team C: *…*

…Again, the same idea with this [second prototype] as with the last one. We'd
have it on a swivel, so you can choose the direction. One of the things that we're
Caregiver: *very interested in is if you rigidly bound the swivel to a handle-*
When he drags his left hand, because it's higher functioning… if he's trying to
drive and control a switch at the same time, that would be difficult unless there's
Team C: *something on it close to his joystick so he could put it in stop. Are you thinking of*
a static [action]?
It's totally controlled by his right hand. We would be putting some sort of lever
Caregiver: *here-ish, and then as you pulled it this way that would turn the frame to the*
Team C: *direction you wanted to go. Then, we can put a button on the end of it, or a*
User: *trigger, and when you push the button you get [the action].*
Caregiver: *Yeah. I think he could do something in this plane right here. No problem.*
Team C: *Which [prototype] do you like?*
Something like this [second prototype]. Seems more understandable to me…
I think it seems more like a natural [action].
Sure. We can work around this one.

This example highlights several different ways that Team C helped their user and associated caregivers understand the design project in order to solicit more in-depth feedback on their current ideas. First, Team C updated their user and associated caregivers on their progress since the last meeting and how they had used the user's input from this previous meeting. Team C thus drew a connection from their last meeting to their current one, demonstrating the value of the user's and caregivers' contributions and clarifying their role in the design project. Team C then described how the purpose of the current meeting was to solicit feedback on a couple of solution concepts that the team had "prototyped." Since their user and associated caregivers were unfamiliar with the terminology of "prototypes," Team C clarified that their prototypes were objects meant to roughly illustrate their current design ideas. This clarification helped Team C's user and their associated caregivers understand both what a prototype was and what sort of feedback might be most useful; they were thus able to justify their preferred solution concept with specific reference to how each prototype functioned.

Conversely, the following example of the *assume stakeholder's or domain expert's understanding* behavior demonstrates how *collaborative* behaviors that were less similar to recommended best practices made it more difficult for stakeholders or domain experts to provide relevant responses. This excerpt features Team D, who was modifying a building associated with the university. During this meeting, Team D hoped to clarify the goals of their project with their project sponsor. They did so by asking questions such as the following:

Team D: *Okay.* ***So, with that in mind, we'd like to know by which criteria the project will be judged. Is there a preferred method you have by which the [issue] should be quantified?...***

Sponsor: *So, first of all, I think quantifying it is a great thing. Obviously we don't have the real time opportunity during the semester to have [the space] full of people… But I would assume... and again, I have no background at all in engineering… I would assume you could model, kind of, expectations of [the issue]. And then, based on what you recommend, say, "This will absorb x percentage." I don't know what that looks like… But I think that's probably the best way to judge it… But also, taking* *into account [other stakeholder] feedback and the aesthetics with [other stakeholders].*

Team D: ***So, I think with the project description, we're mainly doing a prototype. Is a prototype something we'll be installing, and then we'll be able to kind of understand the impact of it?*** *Because we won't be doing the full on project, correct?*

Sponsor: *Yeah. Again, that's something beyond my scope of knowledge, as far as what a prototype might do… But, over the summer, if there's equipment we need to test we can definitely do that…*

Here, Team D asked several questions using technical language around quantification and prototyping that was inaccessible to their project sponsor. The project sponsor thus qualified each of his responses by pointing out that he did not have a technical background before attempting to answer Team D's questions in vague terms. Placing an emphasis on quantification also meant that Team D missed an opportunity to probe deeper into other potential project criteria, such as aesthetics, about which their project sponsor could have provided a more informed response.

5.5 Discussion

5.5.1 Student information gathering behaviors in context

We identified 22 information gathering behaviors that students exhibited when meeting with stakeholders and domain experts to inform their capstone projects. We categorized these behaviors in two primary ways. First, we classified behaviors as either *structural*, *exploratory*, or *collaborative* based upon similarities that we saw across the behaviors in terms of the types of information elicited and the types of meeting situations during which students demonstrated each behavior. Second, we defined behaviors as being either more similar to recommended best practices or less similar to these best practices. These two types of categorization highlight unique aspects of capstone student information gathering approaches.

Student information gathering meetings with stakeholders and domain experts in a capstone design context exhibit characteristics of many different types of engagements, such as informational interviews and collaborative project meetings, that have traditionally been discussed separately in the literature. For instance, many of the behaviors that we categorized as *exploratory* corresponded primarily to recommended best practices (e.g., using open-ended questions to elicit detailed descriptions of experiences) for conducting effective information gathering interviews (IDEO, 2015; Kouprie & Sleeswijk Visser, 2009; Wooten & Rowley, 1995). By comparison, many of the behaviors that we categorized as *collaborative* corresponded primarily to recommended best practices (e.g., developing a mutual language) for collaborating effectively with stakeholders as fellow design project participants (Adams et al., 2018; Kleinsmann et al., 2007; Lehoux et al., 2011). Almost all meeting recordings submitted by participants included both *exploratory* and *collaborative* behaviors as students employed various strategies to understand stakeholder or domain expert perspectives and solicit relevant design feedback. The categorization scheme described in this study thus reflects the composite nature of student information gathering meetings in a capstone design context, as also discussed in Mohedas et al. (2020), and highlights the various types of best practices that students may need knowledge of to conduct these meetings effectively.

In addition, our 11 pairings of behaviors that were less similar to recommended best practices with those that were more similar to recommended best practices may represent student information gathering "learning progressions" towards ideal pedagogical outcomes (Crismond &

Adams, 2012). The collection of behaviors that were less similar to recommended best practices represent "low anchors" describing the baseline knowledge or skills that student designers may possess related to gathering information from stakeholders or domain experts. Many of these "low anchor" behaviors also resemble previous descriptions of different ways that student designers may struggle to conduct effective information gathering meetings (Bano et al., 2019; Luck, 2007; Mohedas et al., 2014). Conversely, the collection of behaviors that were more similar to recommended best practices represent "high anchors," or specific learning gains and approaches that we would hope students exhibit when gathering information. All teams in this study demonstrated both "high anchor" and "low anchor" behaviors to some extent, thus highlighting information gathering best practices that students seemed to be applying successfully as well as specific knowledge gaps.

5.5.2 Impact of different student information gathering behaviors

We did not directly assess how different behaviors impacted the quality or content of information that students gathered from stakeholders and domain experts. However, the in-depth descriptions of student behaviors discussed in this study provide some indication of expected impacts, particularly the likelihood of students eliciting *unknown knowns* or *unknown unknowns* from stakeholders and domain experts. *Unknown knowns* represent relevant information that stakeholders or domain experts may possess but do not immediately articulate; the information may exist in the form of tacit knowledge or may be suppressed for political, social, or emotional reasons (Sutcliffe & Sawyer, 2013). *Unknown unknowns*, by comparison, represent relevant information that is unknown and inexpressible for both the student team and the stakeholder or domain expert; this gap may exist due to a collective lack of knowledge or due to inadequate problem exploration by the student team (Sutcliffe & Sawyer, 2013). Failure to uncover *unknown knowns* and *unknown unknowns* may limit students' understanding of stakeholder needs and/or lead students to develop stakeholder requirements that fail to reflect crucial aspects of these needs (Bursic & Atman, 1997; Loweth et al., 2019; Sutcliffe & Sawyer, 2013).

While there is no way to guarantee that students will uncover *unknown knowns* or *unknown unknowns*, information gathering behaviors that are more similar to recommended best practices may increase the likelihood that this information is uncovered. For instance, *exploratory* behaviors may help students uncover *unknown knowns* by diving deep into stakeholder perspectives and use contexts (IDEO, 2015; Kouprie & Sleeswijk Visser, 2009; Wooten & Rowley, 1995). *Collaborative* behaviors may help stakeholders or domain experts articulate *unknown knowns* of their own initiative (Adams et al., 2018; Luck, 2018; Østergaard et al., 2018). Both types of behaviors may also help students discover *unknown unknowns* as they collect additional information about their design problem. By comparison, the *exploratory* behaviors exhibited by teams in this study that were less similar to recommended best practices may constrain the range of stakeholder or domain expert responses. The *collaborative* behaviors that were less similar to recommended best practices may make it difficult for stakeholders or domain experts to express themselves and contribute relevant information. Both outcomes may decrease the likelihood of uncovering *unknown knowns* or *unknown unknowns*.

5.5.3 Limitations

One limitation of our study was the relative lack of diversity across our participants, with 83% identifying as male and 71% identifying as White. A more diverse group of participants might have interacted with stakeholders or domain experts in ways that were different from the interactions that we observed in our data, which would have potentially led us to define our information gathering behaviors differently. Future work could study how a more diverse group of students interacts with stakeholders or domain experts when gathering information.

In addition, we did not measure the outcomes of student information gathering behaviors relative to each team's design process or product. While we could identify how certain behaviors may have impacted the immediate conversation, broader implications of these behaviors for each team's project were less clear. Future work might explore how project outcomes, such as user satisfaction, may relate to the information gathering behaviors exhibited by a given team.

5.5.4 Implications for design education and practice

Our findings point to several implications for design pedagogy and practice. Student designers could use the list of 22 information gathering behaviors identified in this study as a tool to improve their information gathering processes. This list indicates 11 ideal information gathering behaviors that students should aim to exhibit in their meetings with stakeholders and domain experts, as well as 11 corresponding behaviors that are less similar to recommended best practices and that students may be unintentionally exhibiting instead. When reflecting on their information gathering meetings, student designers could use this list to identify the information gathering behaviors that they are exhibiting most frequently. This facilitated reflection could help students understand what they are already doing well when gathering information, identify specific areas where they might improve their process, and determine new ways to approach gathering information.

Design instructors could also use the findings from our study to develop targeted pedagogy related to conducting effective information gathering meetings. For example, as also noted in Mohedas et al. (2020), the composite nature of student information gathering meetings in a capstone design context means that capstone students would likely benefit from instruction that covers both *exploratory* and *collaborative* information gathering practices. Such instruction might describe effective methods for soliciting deep information (IDEO, 2015; Kouprie & Sleeswijk Visser, 2009) and also for facilitating stakeholder or domain expert design participation (Adams et al., 2018; Østergaard et al., 2018). In addition, our in-depth descriptions of student information gathering behaviors that were less similar to recommended best practices highlight specific student struggles and/or knowledge gaps that may be transferrable to other design contexts and that design instructors could address. For instance, many of these behaviors may have resulted from difficulties that participants experienced while planning out their information gathering meetings. Student designers may thus benefit from additional tools and support that can help them develop well-structured open-ended questions and identify multiple potential follow-up questions that will enable them to gather more comprehensive information from stakeholders and domain experts.

5.6 Conclusion

We identified and described 22 information gathering behaviors that student designers exhibited when meeting with stakeholders and/or domain experts. We defined these behaviors in terms of 11 behaviors that were more similar to recommended best practices for gathering information and 11 behaviors that were less similar to these best practices. Each pair of behaviors represented preferred ways that students might gather information, as well as less ideal practices that students may exhibit instead. In addition, we also classified student information gathering behaviors into three categories, *structural*, *exploratory*, and *collaborative*, based upon similarities in the types of information elicited by each behavior and the types of meeting situations during which students demonstrated each behavior. These categories highlight the composite nature of student information gathering meetings as exhibiting characteristics of both informational interviews and collaborative project meetings. In conclusion, student designers might use the list of behaviors described in our study to help them reflect on and improve their information gathering approaches to be more in line with recommended best practices. Design instructors might use the in-depth case examples presented in this paper to develop targeted pedagogy related to gathering information from stakeholders and domain experts. The findings from our study can thus help student designers gather information more intentionally and effectively as part of their design projects, and as a result develop a deeper understanding of the stakeholder needs that may be driving their design problem and the stakeholder requirements that must be met for their solution to be successful.

5.7 References

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Chapter 6 A Comparative Analysis of Information Gathering Meetings Conducted by Novice Design Teams Across Multiple Design Project Stages[12]

6.1 Introduction

Information gathering activities are core parts of engineering design processes. Designers rarely begin design work with sufficient knowledge about their problem context to develop successful solutions (Goel & Pirolli, 1992; Sutcliffe & Sawyer, 2013). As such, information gathering activities play an important role in enabling designers to define their design problems and evaluate solution feasibility (Dieter & Schmidt, 2013; Pahl & Beitz, 2007; Ulrich & Eppinger, 2012). There are many methods that designers may adopt to gather information, including meeting with project stakeholders and domain experts, benchmarking existing products, searching academic research and patent databases, and researching relevant engineering standards (Dieter & Schmidt, 2013; Nuseibeh & Easterbrook, 2000; Pahl & Beitz, 2007; Rosenthal & Capper, 2006; Sutcliffe & Sawyer, 2013; Ulrich & Eppinger, 2012; Zowghi & Coulin, 2005).

Meetings with stakeholders and domain experts – including, but not limited to, informational interviews, project planning meetings, and collaborative design sessions or workshops – can have a unique impact on engineering design outcomes compared to other types

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of information gathering methods. For example, previous studies have shown that stakeholders can provide specific, in-depth information about their needs and lived experiences that may challenge the preconceived notions of designers (Coleman et al., 2016; Luck, 2018; Rosenthal & Capper, 2006; Sanders & Stappers, 2008). Recommended practices for conducting effective information gathering meetings include soliciting diverse perspectives (Coleman et al., 2016; Deininger et al., 2019; Ogbonnaya-Ogburu et al., 2020; Rosenthal & Capper, 2006), using appropriate information gathering techniques during meetings (Adams et al., 2018; Kouprie & Sleeswijk Visser, 2009; Mazzurco et al., 2018; Zowghi & Coulin, 2005), and conducting multiple information gathering meetings with key stakeholders over time (Agid & Chin, 2019; Lai et al., 2010; Tiong et al., 2019). These practices can help designers elicit useful and comprehensive information through their meetings.

The development of engineering design expertise related to conducting information gathering meetings has been relatively underexplored in the literature. Few comprehensive studies of novice engineering designers' approaches exist that simultaneously explore the types of individuals from whom novice engineering designers gather information, the techniques employed by novice engineering designers to solicit information, and the quantity and timing of their meetings. As a result, there may be specific aspects of novice engineering designers' approaches to conducting information gathering meetings that diverge from recommended practices and that prior work has not described in depth. To address this research gap, our study analyzed data related to information gathering meetings conducted by novice mechanical engineering designers in their culminating design experience prior to becoming engineering practitioners.

6.2 Recommended practices for conducting information gathering meetings to inform design projects

The phrase "information gathering meetings" represents an inclusive way to describe a range of conversation-based interactions between designers and stakeholders or domain experts that designers use to gather design-relevant information. The literature we reviewed includes those related to interviewing best practices (e.g., Spradley, 1979; Wooten & Rowley, 1995) and interviewing for empathy (e.g., Kouprie & Sleeswijk Visser, 2009; Stappers et al., 2009), as well as stakeholder engagement (e.g., Luck, 2018; Østergaard et al., 2018) and design ethnography (e.g., Crabtree et al., 2012; Rosenthal & Capper, 2006) more broadly.

Previous studies and textbooks in the fields of engineering design, design ethnography, requirements engineering, and human-computer interaction (HCI) have provided several recommendations to guide engineering designers in conducting effective information gathering meetings. We synthesized these recommendations into three distinct recommended practices: 1) solicit diverse perspectives, 2) use appropriate information gathering techniques, and 3) conduct multiple meetings over time. Our subsequent discussion of background literature includes recommendations related to each practice and highlights some of the ways that these practices may influence one another.

Recommended practices include that designers should conduct information gathering meetings with multiple individuals possessing various knowledge and representing diverse viewpoints. Engineering design textbooks (Dieter & Schmidt, 2013; Pahl & Beitz, 2007; Ulrich & Eppinger, 2012) suggest that designers should meet with both stakeholders (i.e., individuals that will be directly or indirectly affected by project outcomes) and domain experts (i.e., researchers or practitioners who possess project-relevant engineering expertise) to inform their design decisions. Rosenthal and Capper (Rosenthal & Capper, 2006), in their review of ethnographic methods used across 14 different product design contexts, echoed this point by highlighting the range of different consumers and professionals that designers may consult to inform their design decisions. Studies further show that differences in stakeholder or domain expert characteristics, for instance related to age and physical ability (Coleman et al., 2016; Stappers et al., 2009), personal or cultural values (Brewer & Dourish, 2008; Harrington et al., 2019; Loweth, Daly, Liu, et al., 2020; Rosenthal & Capper, 2006), social status within a larger community (Erete et al., 2018; Harrington et al., 2019; Loweth, Daly, Liu, et al., 2020; Mattson & Wood, 2014; Ogbonnaya-Ogburu et al., 2020), and professional background (Bucciarelli, 1994; Deininger et al., 2019; Lamsweerde et al., 1998), can lead different individuals to provide significantly different and sometimes contrasting descriptions of experiences or feedback on design concepts. By sampling diverse perspectives, designers may be able to identify and account for a wider range of stakeholder needs and requirements while designing. However, as emphasized by Ogbonnaya-Ogburu et al. (2020) in their HCI work, designers must also reflect on how their personal identities (e.g., race, gender, socioeconomic status) may influence the willingness of stakeholders with dissimilar identities to share information during meetings. Designers that lack this self-awareness risk perpetuating existing societal inequalities with their design solutions, even in cases where they solicit diverse stakeholder feedback.

Furthermore, designers should employ information gathering techniques during meetings that are appropriate for the information that they hope to gather. Common techniques include exploring an individual’s knowledge or experiences using a structured interview protocol (Kouprie & Sleeswijk Visser, 2009; Spradley, 1979; Wooten & Rowley, 1995; Zowghi & Coulin, 2005), inviting stakeholder participation in design activities to leverage stakeholders’ unique knowledge and experiences (Harrington et al., 2019; Luck, 2018; Mattson & Wood, 2014; Østergaard et al., 2018; Zowghi & Coulin, 2005), and developing a mutually-accessible design language with stakeholders to facilitate problem co-exploration (Adams et al., 2018; Lehoux et al., 2011; Sanders & Stappers, 2008). Designers may also leverage design representations such as prototypes during information gathering meetings, for instance to facilitate communication with stakeholders or domain experts (Bucciarelli, 2002; Rodriguez-Calero et al., 2020; Sanders & Stappers, 2008) or explore stakeholders' preferences (Rodriguez-Calero et al., 2020; Stappers et al., 2009; Tiong et al., 2019).

Different information gathering techniques differently affect the types of information that stakeholders and domain experts may be able or willing to share during information gathering meetings. For example, while semi-structured exploratory interviews can obtain deep insights about specific experiences, they are not always effective tools for eliciting knowledge that is tacit or otherwise difficult to articulate (Crabtree et al., 2012; Sutcliffe & Sawyer, 2013; Zowghi & Coulin, 2005). Mazzurco, Leydens, and Jesiek (2018), based on their review of community engagement methods in design for development contexts, suggested that highly participatory (or "coconstructive") information gathering techniques enable stakeholders to present their perspectives in authentic ways that can reveal otherwise inexpressible knowledge. Aguirre, Agudelo, and Romm (2017), in their study of co-creative service design events, have also noted that different participatory information gathering techniques encourage different types of thinking (e.g., abductive thinking vs. perspective-taking) and thus elicit different types of stakeholder or domain expert responses.

The appropriateness of certain information gathering techniques also depends upon the characteristics of the stakeholders or domain experts from whom designers are gathering information. For instance, in a study of engineering design interviewing, Deininger et al. (2019) demonstrated that stakeholders with different levels of relevant domain knowledge may differ in their ability to provide in-depth and useful responses during exploratory interviews. Designers may thus need to adapt their information gathering techniques to best suit the individuals from whom they are gathering information.

Recommendations also include conducting multiple information gathering meetings with key stakeholders over the course of design projects. Studies suggest that soliciting stakeholder perspectives throughout problem definition (Mattson & Wood, 2014; Mohedas et al., 2015) and concept development processes (Häggman et al., 2013; Lai et al., 2010; Stappers et al., 2009; Tiong et al., 2019) can help designers develop more appropriate solutions. For example, Tiong et al. (2019) investigated the use of prototypes in the development of three different financial technology business-to-consumer products to identify prototyping approaches that were economically optimal. Their findings emphasized that designers should create low-fidelity prototypes early in their design processes to test their assumptions and uncover users' mental models and then utilize higher fidelity prototypes during later design stages to gather more detailed information. In addition, conducting multiple meetings with the stakeholders can facilitate rapport-building and lead stakeholders to provide more open responses in later meetings (Erete et al., 2018; Le Dantec & Fox, 2015; Spradley, 1979). Agid and Chen (2019), in their study of community-engaged, collaborative design projects, and Pahl and Beitz (2007), in their textbook on engineering design, also emphasized that stakeholder perspectives on needs and requirements often change over time. As a result, designers may need to meet with stakeholders several times to gain comprehensive information.

In some cases, designers may influence changes in stakeholder perspectives through their choices of information gathering techniques. For instance, previous studies have documented how participatory information gathering techniques, when used by designers across multiple meetings, may lead stakeholders to develop new design knowledge that in turn influences their perspectives of the design problem (Agid & Chin, 2019; Østergaard et al., 2018; Taffe, 2015). In such situations, stakeholders may provide new and unexpected information. As an example, Taffe (2015) examined how end-users in a service design context responded to a series of three co-design workshops and, contrary to expectations, found that workshop participants began imagining the needs of other end-users rather than discussing their own experiences. Designers should thus consider how their information gathering techniques in earlier meetings may impact stakeholder or domain expert responses in later meetings.

6.3 Novice designer approaches to conducting information gathering meetings

Studies of novice design approaches provide an informative lens for understanding the evolution of design expertise. For example, studies such as Luck (2007) and Deininger et al. (2017) analyzed novice design approaches to better understand the baseline knowledge or skills that designers may possess related to gathering information. Luck (2007) found that novice architects struggled to adopt stakeholder language when gathering information, while Deininger et al. (2017) found that novice engineering designers struggled to leverage tools such as prototypes effectively to gather information. Other studies by Loweth et al. (2020) and Bano et al. (2019) documented additional challenges encountered by novice engineering designers while gathering information, such as difficulties formulating open-ended questions and exploring stakeholder or domain expert experiences in depth.

Previous studies also observed significant variation among novice engineering designers' approaches to gathering information. For example, novice engineering designers have been shown to vary in the amount of information that they gather to define their design problems (Atman et al., 2007; Mohedas et al., 2015) as well as the timing and quantity of information gathering meetings that they conduct over the course of their design projects (Lai et al., 2010; Loweth et al., 2019). Notably, differences in design context do not seem to explain these observed variations, since participants in the aforementioned studies were working on the same or very similar design tasks. Zoltowski et al. (2012) and Loweth et al. (2019) also showed that novice engineering designers possess varying perspectives regarding the value of stakeholder input to inform their projects. These perspectives may influence when and how novice engineering designers conduct information gathering meetings.

However, previous findings provide only partial insights regarding novice engineering designers' information gathering approaches since few studies have described the content of novice designers' information gathering meetings in depth. Studies such as those by Luck (2007) and Loweth et al. (2020) that identified specific techniques used by novice architects and engineering designers to gather information provided no indication of how often novice designers employed these techniques. Previous studies that explored other aspects of novice information gathering approaches, such as the quantity and timing of conducted meetings (e.g., Lai et al., 2010) or the different types of individuals from whom novice engineering designers gathered information (e.g., Menold et al., 2019; Mohedas et al., 2014), did not analyze data on the content of novice engineering designers' meetings that might explain differences in approaches or experiences observed across participants. Deep exploration of novice engineering designers' information gathering meetings is needed to further understandings of novice information gathering approaches and to reveal additional knowledge gaps that training, tools, and pedagogy can be developed to address.

6.4 Research Design

6.4.1 Research questions

The goal of our study was to understand how novice engineering design teams conducted information gathering meetings to inform their design projects. Our study was guided by the following research questions:

1. With whom do novice engineering design teams meet to gather information?
2. When do novice engineering design teams conduct information gathering meetings?
3. How do novice engineering design teams solicit information during their information gathering meetings?

6.4.2 Participants and context

Participants included 24 students from six design teams enrolled in a single-semester senior-level mechanical engineering capstone design course at a large Midwestern university. This capstone course represented a culminating educational experience that was meant to prepare students to enter professional engineering practice. The design behaviors that participants exhibited in this capstone context are thus likely indicative of how they would approach their early-career design work. Our sample size was appropriate for the in-depth research methods leveraged and was larger than comparable studies (e.g., Mohedas et al., 2014; Safin et al., 2021) of design team communication and information gathering that investigated one to three teams.

Each design team was composed of three to five undergraduate students who were majoring in mechanical engineering and who had completed the required two-course mechanical design sequence. Many participants also described additional design experiences in curricular, co-curricular, and internship settings. However, only one participant reported prior experiences conducting information gathering meetings to inform design projects, since this material was not a focus in participants' earlier mechanical design courses. The composition of the six participating teams and their project foci are included in Table 6.1. Table 6.1 also includes information about the number of information gathering meetings conducted by each team; this information is discussed in greater depth in Section 6.4.3.

Table 6.1 Capstone team project focus and composition, and the number of information gathering meetings conducted by each team. Note: Each capstone section was led by a different instructor.

Team	Capstone section	Type of project	Sex of team members	Race/Ethnicity of team members	Meetings recorded out of meetings conducted
A	1	Developing assistive device	1 Female, 2 Male	1 Asian, 1 Hispanic, 1 White	3 out of 4
B	1	Developing assistive device	1 Female, 4 Male	3 Asian, 2 White	2 out of 5
C	1	Developing assistive device	1 Female, 4 Male	2 Asian, 3 White	4 out of 8
D	2	Modifying university space	1 Female, 3 Male	4 White	5 out of 8
E	2	Developing measurement tool	3 Male	3 White	5 out of 7
F	2	Modifying university space	4 Male	4 White	1 out of 4

Each team was tasked with developing a prototype to solve a unique design problem experienced by a local sponsoring group or organization. Teams worked on one of three types of projects (all project descriptions have been anonymized to protect student and stakeholder identities):

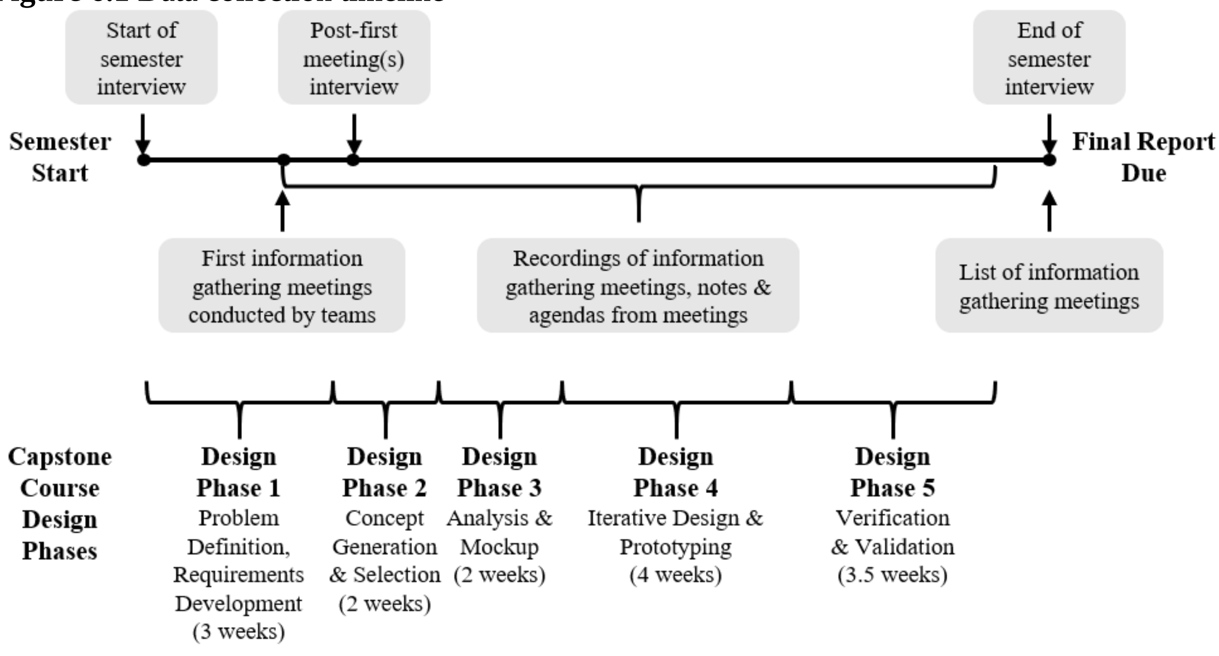
Developing assistive device: Teams A, B, and C were developing assistive devices to help young adults with physical disabilities complete day-to-day tasks, with each team working on a separate project. Each team received an initial project description such as the following: "*[Task] seems like a simple mechanical task, but in fact it requires very complex motion and sensory information processing. This project is focused on creating a new, low-cost device which can be employed by wheelchair users and can adapt to [a variety of situations]. The device will* *be electrically/pneumatic powered and will require minimal tele-operation…*" In addition to a project sponsor, each team was also assigned a specific user who would use their device. All three project topics had been partially addressed in a previous semester by other capstone teams, but none of the solutions produced in this previous semester fully met the users' needs. As such, significant design iterations were still necessary for all three projects, and Team C in particular chose to generate and develop completely new solution concepts.

Modifying university space: Teams D and F were proposing solutions to address chronic issue experienced by different buildings associated with the university. Initial project descriptions of this type resembled the following: "*[The building location] is owned and operated by [university organization], and is located in [Midwestern town]. The [building] is used by [a variety of people], and [the issue becomes most severe] during times of heavy use. The goal of this project would be to make recommendations for improvements to the space [to address the issue], and possibly demonstrate a proof-of-concept prototype(s)…*" As part of their projects, Teams D and F were both tasked to create detailed plans describing how their project sponsors should upgrade their respective buildings using pre-existing materials or technologies. They were also encouraged to develop physical and/or virtual prototypes to demonstrate the efficacy of their improvement plans.

Developing measurement tool: Team E was developing a measurement tool to evaluate the safety of a common consumer product. Their initial project description was as follows: "*Design a tool to test [the displacement] made when [the user is contacting the consumer product]. Ideally, the tool should be easily transportable so that investigators can employ it at investigation sites. In the past, researchers have tried to create a measurement device... [However,] this [previous] tool is limited because the measurement is not precise, it is not a* *good approximation of what happens when [the user contacts the consumer product], and it has low reliability*."

As part of the capstone course, team projects proceeded through five main design phases. Teams submitted a design report at the end of each phase. Design Phase 1 focused on problem definition and requirements development. Design Phase 2 focused on concept generation and selection. Design Phase 3 focused on engineering analyses and development of solution prototypes. Design Phase 4 focused on iterative design and testing of prototypes. Design Phase 5 focused on verification and validation of prototypes, and teams submitted final reports summarizing their work across the semester at the end of this last phase. The relative duration and sequencing of these design phases is shown in Figure 6.1. Although each team received an initial project description at the beginning of the course, this project description did not provide all the information needed to develop an effective solution. As such, the capstone context provided an opportunity to study how novice designers gathered additional information related to their design projects through in-person, phone, and video meetings across multiple design stages.

Figure 6.1 Data collection timeline



Teams attended two lectures during Design Phase 1 related to gathering and utilizing stakeholder and contextual data to inform their design projects. The first lecture described recommended practices for conducting design interviews (primarily drawn from Doorley et al., (2018) and Mohedas et al. (2014)) and provided suggestions for identifying project stakeholders (primarily drawn from Pouloudi & Whitley (1997)). The second lecture discussed recommended practices for synthesizing stakeholder data into design deliverables such as requirements and specifications (primarily drawn from Dieter & Schmidt (2013 and Garvin (1987)). In addition to these two lectures, teams were strongly encouraged to consult auxiliary resources related to conducting design interviews that were available through the University of Michigan's Center for Socially Engaged Design (*Socially Engaged Design Academy*, n.d.). The capstone course was also divided into multiple sections, two of which were represented in this study. Each section was led by a different mechanical engineering instructor who provided design feedback to teams throughout the semester during weekly project meetings and in response to submitted design reports and student presentations.

Although material related to gathering and utilizing stakeholder and contextual data was primarily covered during Design Phase 1, teams were strongly encouraged to meet with stakeholders and domain experts throughout their projects, for example to validate their user requirements, to solicit feedback on their proposed solutions, and to refine details of their solutions. Aside from a course-required initial sponsor meeting, teams arranged stakeholder or domain expert meetings throughout the semester at their own discretion and/or in response to feedback from their capstone section instructor.

6.4.3 Data collection

We collected several types of data from participants, including 1) semi-structured researcher interviews with participants, 2) recordings of information gathering meetings conducted by participants, and 3) a list of information gathering meetings conducted by each team. A timeline of these data collection activities is included in Figure 6.1.

Through three rounds of semi-structured researcher interviews, we collected data about the individuals from whom each team gathered information, when these meetings occurred, the approaches that teams adopted in preparing for and conducting their meetings, and the ways that teams used the information gathered from their meetings. The first interview occurred at the beginning of the semester and was completed with each participant individually. The second interview occurred after teams conducted their first information gathering meetings and was completed in a group setting with all participating members of the team. The third interview occurred at the end of the semester once teams had mostly finished conducting information gathering meetings and was again completed in a group setting with all participating members of the team. Interview protocols were developed for each researcher interview to ensure comparability across responses (Leydens et al., 2004; Maxwell, 2013), and each protocol was piloted with undergraduate students who had relevant prior experiences to help iterate on interview questions in advance. In total, our study collected 20 hours of audio data from researcher interviews with participants.

In addition, across teams, participants recorded 20 out of the 36 information gathering meetings that they reported conducting as part of their capstone projects. These meetings represented 14 total hours of audio data. A breakdown of the total number of reported meetings and submitted recordings per team is included in Table 6.1. The average recording length was 41.7 minutes, with a median recording length of 35.1 minutes. The interquartile range across meeting lengths (which we used to define the length of a “typical” interview in our analysis) was 27.9 minutes to 58.3 minutes. The shortest recording submitted by participants was 4.2 minutes, while the longest was 83.9 minutes. Each team also submitted notes and agendas from their meetings, as well as a list containing the dates and individuals present at all meetings that the team conducted (both in person and over audio or video calls) to inform their projects. Team lists and meeting agendas enabled us to confirm participant interview responses regarding the timing of their meetings and the individuals present at their meetings.

6.4.4 Data analysis

The first step in our data analysis was to categorize the types of individuals from whom teams gathered information (addressing RQ1), based on participant descriptions of these individuals in researcher interviews. Teams described gathering information from a variety of individuals, and our goal was to develop categories of individuals that applied across teams. For example, several teams described gathering design feedback from individuals such as sponsors or other stakeholders who were closely related to their design projects. Since several of these individuals seemed to participate in design decision-making, we collectively categorized these individuals as “project partners.” Once our full list of categories was defined, we then reviewed our data again and classified each of the individuals that teams mentioned in their interviews and meeting lists according to one of the identified categories.

Next, we generated timelines mapping out each team’s information gathering process (addressing RQ2). These timelines were based on the list of information gathering meetings submitted by each team and elaborated upon using meeting descriptions from researcher interviews.

Finally, to characterize how teams solicited information during their meetings (addressing RQ3), two researchers coded the 20 meeting transcripts using the list of information gathering behaviors described in Loweth et al. (2020). This list contained 22 behaviors, half of which were more similar to recommended practices for soliciting information during information gathering meetings and half of which were less similar. Behaviors that were more and less similar to recommended practices were also sorted by Loweth et al. (2020) into 11 pairings such as *encourage deep thinking – elicit shallow responses*; *delve into stakeholder or domain expert experiences – conflate student and stakeholder or domain expert experiences*; and *use a co-creative meeting strategy – use a student-centered meeting strategy*. These pairings facilitated our ability to discern between different information gathering behaviors when coding our data. For example, we coded instances of participants asking open-ended questions to explore specific stakeholder or domain expert experiences or knowledge as *delve into stakeholder or domain expert experiences*. Instances where participants mentioned that their own experiences likely resembled the stakeholder or domain expert's and thus did not ask further questions were coded as *conflate student and stakeholder or domain expert experiences*. Similarly, we coded instances of participants asking open-ended questions that encouraged stakeholders or domain experts to think critically about a topic as *encourage deep thinking*. Closed-ended questions that seemed to limit stakeholder or domain expert responses were coded as *elicit shallow responses*. An example of our coding approach is shown in Table 6.2.

Table 6.2 Brief example of information gathering behaviors described in Loweth et al. (2020)

Example	Information gathering behavior	Definition of behavior
"For example, if [this class] didn't exist, this problem would be solved by calling a company that specializes in this type of work. What is different about their procedure versus what	*Encourage deep thinking*	Students ask questions that encourage the stakeholder or domain expert to move beyond superficial responses and provide in depth knowledge on subject

we're doing?" (Team D, Phase 2 expert meeting)		
"So, right now, what do you currently do when you encounter [this issue]? Do you just have to wait for someone to help or ...?" (Team B, Phase 2 user meeting)	*Elicit shallow responses*	Students ask questions that implicitly constrain stakeholder or domain expert responses
"You've been part of the industry for a while, so could you share with us a bit of your background and what you specialize in particularly? (Team E, Phase 2 expert meeting)	*Delve into stakeholder or domain expert experiences*	Students evoke specific ideas or experiences of the stakeholder or domain expert to better understand how the individual thinks and feels about the design problem
"We basically would take what the past team has done, except that we wanted to change the connection… because, when we tried to use the prototype they made, it was kind of hard for us." (Team A, Phase 3 partner meeting)	*Conflate student and stakeholder or domain expert experiences*	Students suggest that the stakeholder or domain expert's experiences likely resemble their own and do not explore the individual's experiences in greater depth
"Right now, this is how we're envisioning it, but we obviously want to get your feedback to see if you actually like it or not." (Team C, Phase 4 user & partner meeting)	*Use a co-creative meeting strategy*	Students establish space within the meeting for the stakeholder or domain expert to make project decisions or give design feedback
"The purpose of this meeting is to update you with our design decisions, and we're moving forward with what we came up with." (Team A, Phase 3 partner meeting)	*Use a student-centered meeting strategy*	Students control the goals of the meeting and project, making decisions and informing the stakeholder or domain expert of those decisions rather than soliciting input on those decisions

Our initial round of coding produced a preliminary total for how often each information gathering behavior occurred in each of the submitted meeting recordings. To normalize and compare the frequency with which behaviors occurred across teams, we then developed a four-point ordinal scale to represent behavioral frequencies within each meeting. According to our scale, "none" represented no occurrences of a behavior within the meeting, "present" represented one to two occurrences, "repeated" represented three to six occurrences, and "frequent" represented seven or more occurrences. We defined the four ordinal categories in our scale based upon the size of each team (three to five members) and the typical length of meeting recordings across teams (roughly 30 to 60 minutes). After converting our initial occurrence counts for each information gathering behavior to ordinal rankings, we discussed remaining discrepancies between the two coders' interpretations and refined our rankings for each behavior across the 20 submitted meetings. The two coders then re-coded five meeting transcripts, specifying the frequency of each behavior within a given transcript according to the ordinal scale. Our inter-rater reliability for this re-coding, calculated using Cohen's weighted kappa (Cohen, 1968) to penalize discrepancies greater than a single ordinal step, was 76.7% . This value represents reasonably high agreement between the two coders (Hallgren, 2012), especially since the purpose of our ordinal scale was to facilitate comparison across meeting transcripts rather than define an absolute metric of measurement.

6.5 Findings

6.5.1 Types of individuals from whom novice design teams gathered information

Teams described meeting with four main types of individuals to inform their projects. These types of individuals are summarized in Table 6.3.

Table 6.3 Summary of individuals with whom teams interacted

Type of individual	Description	Teams
Project partners	Members of sponsoring groups/organizations and other closely related stakeholders, typically had non-engineering backgrounds (e.g., the project sponsor or a non-profit volunteer)	A, C, D, E, F
Domain experts	Individuals with substantial engineering/design knowledge relevant to the project (e.g., an engineering professor or outside consultant)	All six teams
Previous team	Students who had worked on the capstone project topic during a previous semester	A, B, C
Users	Individuals with a direct relationship of use with the designed solution	B, C

Five out of six teams described meeting with representatives of the group or organization that was sponsoring their design project and/or other closely related stakeholders, i.e., "project partners." These individuals were either matched to teams through the capstone course as specific "project sponsors" or were invited by project sponsors to participate in team projects.

Project partners typically had non-engineering backgrounds and possessed substantial knowledge about stakeholder needs. All six teams met with "domain experts," or individuals with substantial engineering or design knowledge relevant to the project. These domain experts were usually university professors, although Teams D and E also met with expert consultants. Unlike other teams in our study, Team B's project was initiated by an engineering professor; as such, Team B did not meet with a separate project partner. Teams A, B, and C were working on project topics that had been addressed in a previous semester. All three teams met with individuals from the previous design team (i.e., the "previous team") who were able to discuss previous design decisions and could provide suggestions for future design iterations. Finally, Teams A, B, and C were provided specific "users" as part of their capstone projects. Teams B and C interacted with their user, but not Team A. Teams who were not given a specific user to contact also did not meet with users.

6.5.2 Timelines of information gathering meetings conducted by novice design teams

Teams reported conducting a total of 36 information gathering meetings throughout the semester, with each team reporting between four and eight meetings as shown in Figure 6.2. Many of these meetings (13 out of 36) were conducted during Design Phase 1 while teams were learning about their stakeholders' needs and developing user requirements and engineering specifications. Each team was required by the capstone course to complete at least one information gathering meeting during Design Phase 1, and all six teams ultimately conducted at least two meetings during this phase.

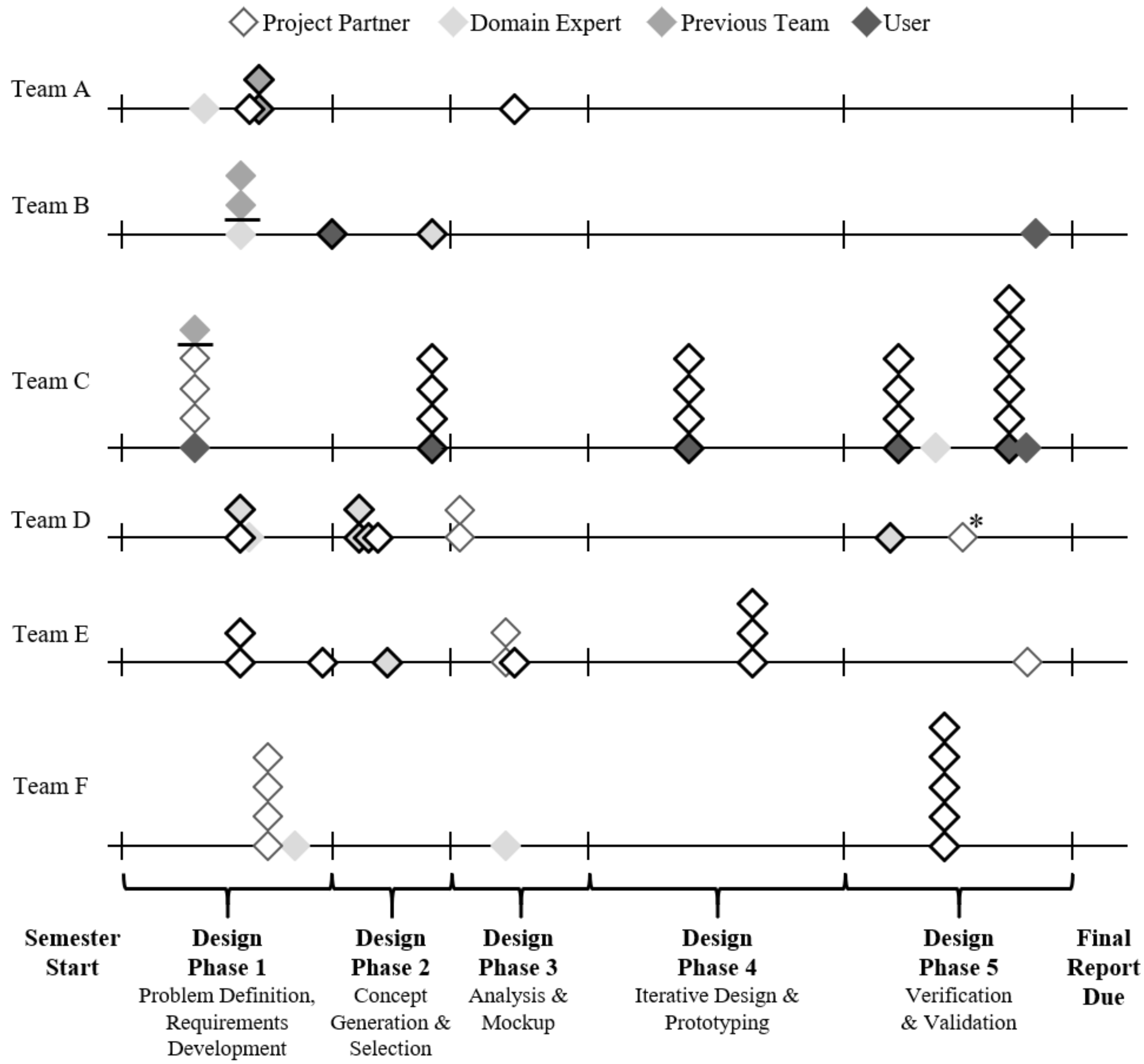
As teams transitioned to developing and selecting solution concepts (Design Phase 2), differences began to emerge in their respective approaches to conducting information gathering meetings. Teams reported seven total meetings during this phase. Teams D and E met with domain experts to gather more information about what types of solutions might be feasible. Similarly, Team B met with their user for the first time to learn more about their user's needs. Teams B, C, and D solicited feedback via an information gathering meeting to help them select a solution concept. Teams A and F did not report conducting any additional information gathering meetings prior to selecting a solution concept to implement.

Teams reported five total meetings during Design Phase 3. Teams A and E updated project partners about their progress and discussed the solution concept that they had chosen. This phase was also the last time that Team A reported conducting an information gathering meeting for their project. Teams D and F each met with new individuals to gather additional information relevant to their solution development processes. Teams B and C did not report conducting information gathering meetings during this phase as they completed their engineering analyses and developed detailed solution mock-ups.

Teams reported conducting only two information gathering meetings during Design Phase 4 as they developed and iterated on their physical prototypes. Team E met with project partners to demonstrate an early version of their prototype and solicit feedback. Team C met with their user and project partners prior to beginning their manufacturing process to gather additional information about their user's physical constraints and solicit further design feedback.

Teams reported conducting nine meetings during Design Phase 5. Team C met with their user and project partners to gather additional contextual information and solicit feedback. Teams C and D also met with domain experts to gather information that could help them implement their final prototype. Lastly, all teams except Team A reported presenting a final iteration of their physical prototype to users and/or project partners prior to submitting their final project report, with Team C conducting two such meetings. Team A did not report a meeting during this phase because they had presented their final concept during Design Phase 3.

Figure 6.2 Timelines of information gathering meetings conducted by participants. Each diamond represents an individual present at the meeting. Meetings that occurred on the same day are separated by bold black horizontal lines. The * symbol for Team D indicates a meeting during which the team sought feedback on their solution concepts from a 12-member advisory board. Diamonds with bold black outlines signify meetings for which teams submitted audio recordings. Diamonds without black outlines signify meetings that were not recorded and thus were not included in our data.



6.5.3 Information gathering behaviors exhibited by novice design teams

Each meeting recording submitted by participants contained a different set of information gathering behaviors. The information gathering behaviors observed within submitted meetings tended to vary based upon the design phase of the meeting, the individuals present at the meeting, and the team who conducted the meeting. A summary of the main meeting contexts where each information gathering behavior was observed to occur and the number of times each behavior occurred per meeting is shown in Tables 6.4 (for behaviors that were more similar to recommended practices) and 6.5 (for behaviors that were less similar to recommended practices). The phrase “occurred sparingly” indicates that a given behavior was not typically observed outside of the explicitly noted meeting context; for example, teams did not typically exhibit the *encourage deep thinking* behavior except in meetings with domain experts. Furthermore, the trends described in Tables 4 and 5 are not mutually exclusive. For instance, Team A typically exhibited the *lead the stakeholder or domain expert to conclusion* behavior one to two times per submitted meeting during Design Phases 1 and 2. They also, along with the other teams in this study, typically exhibited the *verify the conclusions drawn from meetings* behavior one to two times per submitted meeting during Design Phases 1 and 2. Team A’s meetings during Design Phases 1 and 2 thus typically contained both behaviors, as well as the other information gathering behaviors that we have described as occurring across all teams or occurring in Team A’s meetings specifically.

Table 6.4 Summary of main meeting contexts (individuals, design phases, and teams) in which each information gathering behavior that was more similar to recommended best practices for soliciting information was observed. "---" denotes the absence of a behavior in cases where a behavior occurred sparingly.

Information Gathering Behavior	Characteristic of Meeting			Occurrences per Meeting
	Individual	Design Phase(s)	Team(s)	
Build rapport with the stakeholder or domain expert	Project partners	All	All	3-6
	All others	All	All	1-2
Avoid misinterpretations	Project partners or users	Phases 1 & 2	All	3-6
	Project partners or users	Phases 3+	All	1-2
	All others	All	All	1-2
Guide meeting direction while inviting stakeholder or domain expert input	All	All	All	1-2
Encourage deep thinking	Domain experts	All	All	1-2
	All others	---	---	Occurred sparingly
Flexibly & opportunistically probe responses	All	Phases 1 & 2	All	1-2
	---	Phases 3+	---	Occurred sparingly
Verify the conclusions drawn from meetings	All	Phases 1 & 2	All	1-2
	---	Phases 3+	---	Occurred sparingly
Delve into stakeholder or domain expert experiences	Domain experts or users	All	All	3-6
	All others	All	All	1-2
Use a co-creative meeting strategy	Project partners	All	All	3-6
	All others	All	All	1-2
Develop mutual understanding with the stakeholder or domain expert	Project partners	All	Team C	7+
	Project partners	All	All others	1-2
	All others	---	---	Occurred sparingly
Introduce relevant information	All	All	Teams D & E	1-2
	---	---	All others	Occurred sparingly
Explore differences between perspectives	All	All	Teams A, D & E	1-2
	---	---	All others	Occurred sparingly

Table 6.5 Summary of main meeting contexts (individuals, design phases, and teams) in which each information gathering behavior that was less similar to recommended best practices for soliciting information was observed. "---" denotes the absence of a behavior in cases where a behavior occurred sparingly.

Information Gathering Behavior	Characteristic of Meeting			Occurrences per Meeting
	Individual	Design Phase	Team	
Damage rapport	---	---	---	Occurred sparingly
Muddle information received from the stakeholder of domain expert	All	All	Team D	1-2
	---	---	All others	Occurred sparingly
Cede guidance of meeting	Domain experts	All	All	3-6
	All others	All	All	1-2
Elicit shallow responses	All	All	Teams A, B & D	3-6
	---	---	All others	Occurred sparingly
Rigidly adhere to structure	All	All	Teams A, B & D	1-2
	---	---	All others	Occurred sparingly
Lead the stakeholder or domain expert to conclusion	All	Phases 1 & 2	Teams A & B	1-2
	---	---	All others	Occurred sparingly
Conflate student and stakeholder or domain expert experiences	All	All	Team A	1-2
	---	---	All others	Occurred sparingly
Use a student-centered meeting strategy	All	All	Team A	1-2
	---	---	All others	Occurred sparingly
Assume stakeholder's or domain expert's understanding	Project partners	All	All	1-2
	All others	---	---	Occurred sparingly
Introduce unclear information	All	All	Team D	1-2
	---	---	All others	Occurred sparingly
Place own perspective above others'	All	All	Team A	1-2
	---	---	All others	Occurred sparingly

Three behaviors occurred most frequently in meetings that teams conducted during Design Phases 1 (problem definition) and 2 (concept development and selection) of their projects: *avoid misinterpretations* (three to six times/meeting), *flexibly & opportunistically probe responses* (one to two times/meeting) and *verify conclusions drawn from meetings* (one to two times/meeting). Teams exhibited the *avoid misinterpretations* behavior when they asked clarifying questions (e.g., Team C, Phase 2 user and partner meeting: "Do you always wear the seatbelt when you're in the wheelchair?") or repeated previous responses (e.g., Team D, Phase 1 partner and expert meeting: “And then you also mentioned if our prototype was something you put on the wall or ceilings, you mentioned keeping it to the ceiling for the aesthetics.”). Teams exhibited the *flexibly & opportunistically probe responses* behavior when they asked additional questions to follow up on information provided by the stakeholder or domain expert (e.g., Team D, Phase 1 expert meeting: “This is kind of a random question… is there cleaning that is associated with [that solution option]?”) Lastly, teams exhibited the *verify conclusions drawn from meetings* behavior when they checked their understanding of stakeholder or domain expert responses (e.g., Team E, phase 1 partner meeting: “When you say ‘quantitative,’ it seems like that displacement is probably the… most important measurement. Would that be correct to how much the [user] is imprinting into the [consumer product]? Is that the most important metric?”). All three behaviors occurred less frequently in later design phases; participants exhibited the *avoid misinterpretations* behavior only one to two times per meeting after Design Phase 2 and typically did not exhibit the behaviors *flexibly & opportunistically probe responses* and *verify conclusions drawn from meetings*.

Several behaviors occurred mainly with specific types of individuals. The behaviors *build rapport with the stakeholder or domain expert* (three to six times/meeting), *use a co-creative meeting strategy* (three to six times/meeting) and *assume stakeholder’s or domain expert’s understanding* (one to two times/meeting) occurred most frequently in meetings with project partners. The following excerpt from a Design Phase 4 meeting conducted by Team E demonstrates how participants used the behaviors *build rapport with the stakeholder or domain expert* and *use a co-creative meeting strategy* to gather information from project partners. In this case, Team E was seeking feedback on a physical prototype of their safety measurement tool from their partners (specifically, their sponsor and a doctor who was also involved with the project):

Doctor: And then for the weight to mimic [the user]. What are you guys thinking about for how to do that?

Team E: You have a couple options there. We were offered brass in the machine shop. But we were also thinking of using steel pellets, which would be smaller so you can add them and increment the weight slower, or by a smaller factor. We're kind of weighing those two options right now I guess.

Doctor: Oh I get it, you're *weighing* those two options.

Team E: Clever, you caught it.

Sponsor: So you add the weight once [the device] is on the [consumer product]? It's not just a weighted item that you put on it and it goes to wherever it's gonna go?

Team E: Yeah I suppose that's what we're considering. Whether it would be beneficial just to have three to five standard weight options that you can put in. Or if there would be any benefit to getting a reading more continuously… so you could see how it varies with weight a little bit more smoothly. Those are just things we're considering right now.

Sponsor: Yeah, the problem I see with pouring in loose pellets or shot or whatever you're using, is the ... not for you guys, but for future iterations of the project, someone having to keep track of pieces.

This excerpt aligns with the *use a co-creative meeting strategy* behavior in two ways. Team E provided space for their project partners to ask questions related to the function of their prototype. Team E's description of their thought process while considering different weight options also enabled their project partners to provide targeted feedback related to the feasibility of those weight options. Team E's "weighing" joke (i.e., *build rapport with the stakeholder or domain expert*) additionally helped them build their relationship with their partner through this exchange.

By comparison, the *delve into stakeholder or domain expert experiences* behavior typically occurred three to six times in meetings involving either domain experts or users. For instance, participants exhibited this behavior when they asked open-ended, exploratory questions related to an expert's domain knowledge (e.g., Team E, Phase 2 expert meeting: "If there were to be a time when a [measurement] standard was put into there, what would go into that process?") or user's past experiences (e.g., Team B, Phase 2 user meeting: "What were the biggest challenges that you thought [about] using the prototype last semester?"). The behaviors *encourage deep thinking* (one to two times/meeting) and *cede guidance of meeting* (three to six times/meeting) also occurred most frequently in meetings with domain experts. The following excerpt from a Design Phase 5 meeting conducted by Team D demonstrates how participants used the *encourage deep thinking* behavior to gather information from domain experts. In this case, Team D was meeting with an engineering professor from the university to discuss how they might best implement their solution:

Team D: So we were suggesting ... 'Cause the [analysis] that we did showed that the ceiling is the most effective... Like the angled part of the ceiling. And we suggested covering the whole angled part of the ceiling. But [our sponsor] would like to reduce cost.

Professor: Correct.

Team D: And so they wanna do basically the bare minimum that's gonna look good and then effectively improve the [issue]. So we were wondering… if we just build between every other rafter, how would that affect the [issue]?

Professor: Yeah. It's just a reduction of [this parameter]. Let me just reiterate what I said before because I noticed that when you had the source, you had the source in one direction, right? Okay. So if you put the source that goes in all directions, then you will see that, in reality, the walls are the ones that are causing all the trouble for you… So if you're asking me, without measurements, based on my measurements, all the years I have done, the walls are the most trouble makers… [Your solution] helps and contributes, but it may be overpowered by the walls before it [makes a difference].

Team D's question, "How would that affect the issue?", was open-ended and encouraged this engineering professor to think critically about the potential implications of Team D's solution. Team D thus elicited feedback on their validation process and also identified additional considerations that their solution needed to address.

Some behaviors were primarily associated with specific teams. For example, Team C typically exhibited the *develop mutual understanding with the stakeholder or domain expert* behavior more than seven times per meeting, usually to help their user and project partners understand their design project so that they could provide more informed feedback (e.g., Team C, Phase 2 user and partner meeting: "We've put together a couple of our preliminary ideas… put together the design requirements from the feedback you gave us. Based on that, we built a couple of [functional] prototypes we brought to show you today… they're the rough sketch of what we're thinking.”). Team C also rarely exhibited the behaviors *elicit shallow responses* or *rigidly adhere to structure*.

By comparison, Teams A, B, and D typically exhibited the behaviors *elicit shallow responses* (e.g., Team D, Phase 1 partner and expert meeting: “What is it like to go in the [space] for a [visitor]? Can you just tell us what that's like? Do they bring their own [materials]?”) three to six times per meeting and *rigidly adhere to structure* (e.g., Team A, Phase 3 partner meeting: “Okay. So the next item is options for [decoration] and I think we went through that already. Do you have any general feedback on our design, or anything general, just ...”) one to two times per meeting. Teams A and B also typically exhibited the *lead the stakeholder or domain expert to conclusion* behavior (e.g., Team B, Phase 2 user meeting: “So, in regards to carrying [the prototype], currently it weighs 10 pounds. So, is it the weight that's the biggest challenge or is it also the size or ...?”) one to two times per meeting conducted during Design Phases 1 and 2.

Teams D and E typically exhibited the *introduce relevant information* behavior one to two times per meeting (e.g., Team D, Phase 2 expert meeting: “So we've done a lot of preliminary searching, both online and in text books and journals and things like that, to learn about the engineering behind [this issue], and we've met with a couple of experts.”); they, along with Team A, also exhibited the *explore differences between perspectives* behavior one to two times per meeting (e.g., Team E, Phase 2 expert meeting: “So I think [our partners], they're hoping that this device could offer and collect some data that has substantial evidence... Is there anything that we should be looking out for in terms of creating a device that [your committee] would specifically appreciate?). Team D typically exhibited the behaviors *muddle information received from the stakeholder or domain expert* and *introduce unclear information* one to two times per meeting. Team A typically exhibited the behaviors *use a student-centered meeting* *strategy, conflate student and stakeholder or domain expert experiences,* and *place own perspective above others'* one to two times per meeting.

6.6 Discussion

While the teams in our study exhibited diverse approaches to conducting information gathering meetings, we observed several trends across teams. For example, participants exhibited a wide range of information gathering behaviors that aligned with recommended practices, especially during Design Phases 1 and 2. Furthermore, occurrences of information gathering behaviors that were less similar to recommended practices were generally limited across teams, although it is important to note that behaviors such as *damage rapport* or *use a student-centered meeting strategy* can negatively impact stakeholder or domain expert responses in significant ways even after a single occurrence. In addition to these positive trends, we also observed two trends across team approaches that represented specific opportunities for improvement and may reflect characteristic novice approaches to conducting information gathering meetings.

First, we observed that participants seemed to **prioritize domain experts as sources of information**, especially compared to other types of individuals. "Prioritization" was evident in the fact that participants employed deep exploratory behaviors such as *delve into stakeholder or domain expert experiences* and *encourage deep thinking* to a greater extent in meetings with domain experts compared to meetings with other types of individuals such as project partners. "Prioritization" was also evident in the fact that teams contacted and met with additional domain experts who had no previous affiliation with the capstone course or project sponsors (but were readily accessible through the university) to inform their projects. For example, Teams C, D, and F described conducting meetings with engineering faculty who possessed no previous connections to their projects. All users, project partners, and previous team members described by participants either had direct connections to the capstone course (e.g., users provided through the capstone course) or close relationships with project sponsors. This latter observation is unsurprising given that finding additional users or stakeholders would have required a significant time investment for most teams, particularly compared to finding additional domain experts.

Compared to meetings with domain experts, participants' meetings with other types of individuals typically contained fewer occurrences of deep exploratory information gathering behaviors. For instance, five out of six teams met with project partners to inform their projects (Team B was the exception, since their project sponsor was a domain expert). These meetings were characterized by the behaviors *build rapport with the stakeholder or domain expert* and *use a co-creative meeting strategy*. As a reminder, "co-creative" in the context of this information gathering behavior refers mainly to meeting or project goals; teams that exhibited this behavior established space during their information gathering meetings so that stakeholders or domain experts could provide feedback that influenced the meeting and/or project direction. Teams in this study did not typically engage in co-creative ideation and solution development (e.g., as described in Aguirre et al. (2017) and Sanders & Stappers (2008)) with stakeholders or domain experts, and there was not an expectation for them to do so.

As demonstrated by Team E's excerpt in Section 5.3, *use a co-creative meeting strategy* represented an effective method for teams to solicit unstructured feedback on their design approaches and/or solution concepts. However, recommended practices for information gathering (e.g., Kouprie & Sleeswijk Visser, 2009; Spradley, 1979; Wooten & Rowley, 1995) suggest that designers should also deliberately employ exploratory questioning techniques to gather deep information about stakeholder needs and requirements to inform their understanding of their design problems and the feasibility of their solutions. The relative lack of behaviors such as *delve into stakeholder or domain expert experiences* and *encourage deep thinking* in project partner meetings indicates that participants did not consistently use deep exploratory questioning techniques with project partners. As such, even though participants did solicit feedback on their design approaches and solutions, it is unclear to what extent participants fully explored this feedback and/or gathered detailed information about their partners' personal experiences that might inform their understandings of stakeholder needs and requirements.

While it is unclear why participants in our study infrequently employed exploratory questioning techniques to investigate the perspectives of their project partners in depth, there are a few possible explanations. For instance, Häggman et al. (2013) (study involving novice engineering designers) and Sugar (2001) (study involving novice software designers) observed novice designers confirming design decisions during stakeholder meetings while gathering limited additional information about stakeholders' knowledge or experiences. Participants in our study may similarly have viewed their project partner meetings mainly as opportunities to discuss design decisions, but not necessarily as opportunities to solicit deep information related to their partners' knowledge of their design problem. Mohedas et al. (2014) also showed that some novice engineering designers struggled to interpret and apply information from stakeholders, particularly in cases when they received conflicting information from different stakeholders. As such, it is possible that our participants rarely employed behaviors such as *delve into stakeholder or domain expert experiences* and *encourage deep thinking* with project partners because they may have been unsure how to leverage deep stakeholder information effectively to inform their projects.

A related explanation is that participants may have struggled to identify specific, open-ended information goals for their meetings with project partners, especially compared to their meetings with domain experts. For example, the deep exploratory information gathering behaviors exhibited by teams during domain expert meetings seemed motivated by specific *known unknowns*, i.e., important information that the team knew they did not possess (Sutcliffe & Sawyer, 2013), related to technical aspects of their user requirements and/or solution concepts. It is unclear whether participants identified similarly specific and open-ended information goals for their project partner meetings as well. For instance, Team A mainly used their partner meetings to confirm, but not explore, previous design decisions, as reflected in information gathering behaviors such as *use a student-centered meeting strategy*. By comparison, Team E solicited open-ended feedback from their partners but rarely asked prompting questions to guide this feedback in specific directions. Without specific and open-ended information goals for project partner meetings, participants may not have felt a need to employ behaviors such as *delve into stakeholder or domain expert experiences* and *encourage deep thinking* to explore their partners' perspectives in depth.

This hypothesized difference in information goals may also partially explain why participants in our study arranged meetings with additional domain experts, i.e., individuals who might clearly contribute relevant information to inform participants' design decisions, but not other types of individuals whose potential contributions may have been less clear. Mohedas, Sienko, Daly, and Cravens (2020) observed that novice designers in a similar capstone design context resisted meeting with individuals that they perceived as lacking expertise directly related to their design projects. Our participants may similarly have resisted meeting with stakeholders beyond their project partners and assigned users because they may have felt that such meetings would not provide project-relevant information. Alternatively, it is also possible that our participants identified specific and open-ended information goals for stakeholders but were unable to meet with individuals that they felt could provide the needed information. This latter explanation aligns with data from Mohedas, Daly, and Sienko (2014) indicating that novice designers may struggle to find stakeholders who possess the exact information that they are hoping to gather and thus conduct fewer information gathering meetings with stakeholders as a result.

In addition, we observed that participants seemed to **prefer early and decisive information gathering meetings**. In part, this trend was reflected in the timing of participants' information gathering meetings, since teams in our study reported conducting most (20 out of 36 total) of their meetings during their first two design phases focusing on problem definition and concept generation/selection, respectively. In particular, Teams A (three out of four meetings), B (four out of five meetings) and D (five out of eight meetings) each conducted more than 60% of their meetings during their first two design phases. This approach to conducting information gathering meetings contrasts with recommended practices, which suggest that designers should solicit stakeholder feedback consistently throughout their projects (Häggman et al., 2013; Lai et al., 2010; Mohedas et al., 2015; Tiong et al., 2019).

The content of participants' early information gathering meetings also seemed to reflect a preference for decisive decision-making during these meetings. All teams in this study exhibited the behaviors *avoid misinterpretations*, *flexibly & opportunistically probe responses* and *verify conclusions drawn from meetings* in their early meetings. The *avoid misinterpretations* behavior occurred less frequently in later meetings, whereas the behaviors *flexibly & opportunistically probe responses* and *verify conclusions drawn from meetings* essentially did not occur in later meetings. Teams A, B, and D, who each reported conducting more than 60% of their meetings during their first two design phases, additionally exhibited the behaviors *elicit shallow responses*, *rigidly adhere to structure*, and (for Teams A and B) *lead the stakeholder or domain expert to conclusion* in their early meetings.

The collection of information gathering behaviors exhibited by teams in their early meetings suggest that teams used these meetings to establish problem definitions and select preferred solution concepts as quickly as possible. Behaviors such as *elicit shallow responses* and *lead the stakeholder of domain expert to conclusion*, which do not align with recommended practices, served mainly to confirm students' prior notions rather than invite stakeholders or domain experts to provide surprising information. In addition, participants employed the behaviors *avoid misinterpretations*, *flexibly & opportunistically probe responses* and *verify conclusions drawn from meetings* primarily in situations when they sought to solidify their understandings of their design project, for instance to clarify their design requirements or verify their project sponsor's preference for a certain solution concept. While these three behaviors do align with recommended practices – designers should consistently check that their understanding of design information aligns with the perceptions of stakeholders or domain experts (Crabtree et al., 2012; Firesmith, 2003; Loweth, Daly, Hortop, et al., 2020; Nuseibeh & Easterbrook, 2000) and flexibly follow up on interesting responses (Kouprie & Sleeswijk Visser, 2009; Loweth, Daly, Hortop, et al., 2020; Rosenthal & Capper, 2006) – designers should be employing these information gathering techniques *throughout* their design processes. For instance, in later design stages, these techniques might facilitate the collection of comprehensive feedback related to solution prototypes that may further the designer's understanding of their design problem (Häggman et al., 2013; Tiong et al., 2019). Furthermore, stakeholder perspectives could change over the course of a semester, potentially leading stakeholder needs or requirements to change as well. Since participants mainly used the behaviors *avoid misinterpretations*, *flexibly &*

opportunistically probe responses and *verify conclusions drawn from meetings* to solidify their understandings of their design projects, the relative lack of these behaviors in later meetings suggests that teams did not typically revisit their understandings of their design projects over time. In other words, teams may have treated the design decisions made during their first two design phases as final, which may also explain why teams conducted fewer information gathering meetings during later design phases.

There are several reasons why participants in our study may have exhibited a preference for early and decisive information gathering meetings. For example, students were required to develop a working solution prototype by the end of the semester and likely felt that they did not have time to revisit previous design decisions and/or preserve ambiguity in their design approaches. Participants may also have tailored their efforts towards the specific design phase grading criteria, which tended to emphasize engineering analyses and design validation during later design phases.

In addition to these contextual explanations, findings from previous studies also indicate that early and decisive information gathering meetings may be characteristic of novice information gathering approaches more broadly. For instance, Crismond and Adams (2012), based on a synthesis of literature, suggested that novice designers engage in limited exploration of their design problems and start developing final solutions prematurely in their design processes. Rao et al. (2021), in their study of novice engineering designers' decision-making strategies, found that their participants were most focused on exploring user needs and characteristics during early design stages and were less focused on collecting user information during later design stages. Leahy et al. (2020) observed that some novice designers fixated on their own initial ideas for solution concepts during ideation and thus devoted limited time to exploring alternative options. Lastly, Lai et al. (2010) found that novice designers in another curricular design context conducted most of their information gathering meetings during the early stages of their design projects. Our findings thus align with prior observations related to the timing of novice information gathering meetings. Our findings also uniquely highlight the specific information gathering behaviors that novice engineering designers may employ during their initial information gathering meetings to help them finalize design decisions early in their design processes.

While we did not evaluate the outcomes of team projects, previous studies suggest that novice designers who conduct information gathering meetings mainly during the early stages of their design projects are less likely to produce successful design outcomes compared to novice designers who conduct meetings consistently across design stages. Atman et al. (2007), in a study involving three-hour design challenges, found that novice engineering designers who gathered information only at the beginning of their problem solving processes also generated lower quality solutions. Similarly, Häggman et al. (2013), in a study of curricular design projects, observed that novice engineering designers who solicited stakeholder input only at the beginning of their concept development processes developed less successful solutions compared to peers who solicited input throughout their concept development processes. Novice designers who conduct few information gathering meetings beyond their initial design activities may also consult fewer sources of information for their projects overall, and Mohedas et al. (2015) in their study of novice requirements development processes identified a positive correlation between the number of information sources that novice designers consulted and the stakeholder validity of their requirements. These prior findings suggest that our participants' general approach to conducting information gathering meetings, i.e., conducting many meetings during early design phases with limited follow up during later design phases, may overall have been sub-optimal for design success, even though participants employed recommended practices for soliciting information (such as *avoiding misinterpretations*, *flexibly & opportunistically probing responses* and *verifying conclusions drawn from meetings*) during their early meetings.

While the information gathering approaches of most teams in our study aligned with the two trends described above, we did note an important exception: Team C. Team C met with their users and project partners at least once during almost every design phase. These project partners had a range of backgrounds and experiences. Furthermore, Team C's submitted meetings contained frequent instances of the behavior *develop mutual understanding with the stakeholder or domain expert* and few instances of information gathering behaviors that were less similar to recommended practices. Team C thus seemed to adopt an effective approach to conducting information gathering meetings: they solicited multiple perspectives consistently over time using appropriate information gathering techniques.

Notably, Team C did not possess substantially more information gathering experience than other teams in our study. The course-level support that Team C received related to conducting information gathering meetings was also very similar to the support received by Teams A and B, who were in the same capstone section. However, we did observe two key differences related to this team and their project context. First, Team C benefitted from being able to meet with their user and several different project partners simultaneously. This convenience enabled the team to solicit diverse perspectives within the context of a single meeting rather than across multiple meetings. These meetings also provided unique opportunities for Team C to resolve differences between stakeholder perspectives in real time, and this added benefit may have motivated Team C to conduct more meetings with their user and partners. In addition, as described in greater depth in Loweth et al. (2019), Team C repeatedly emphasized the value of stakeholder perspectives as sources of information during their researcher interviews, especially compared to other teams. As such, the case of Team C seems to support a correlation previously theorized by Zoltowski et al. (2012): novice engineering designers who highly value stakeholder perspectives may also be more likely to solicit these perspectives consistently to inform their projects. Our findings further suggest that novice engineering designers who highly value stakeholder perspectives may also employ more effective information gathering techniques during their meetings.

6.6.1 Limitations

One study limitation was our primary focus on meetings as a method of gathering information. There are many other ways to gather information to inform design decision-making, including observations, surveys and academic research. Some participants may also have used email to solicit additional information from stakeholders or domain experts but did not report such email exchanges to the research team.

Teams did not submit recordings for every information gathering meeting that they conducted. Although there were no systematic omissions based on the meeting timing or type of individual involved in the meeting, more meeting recordings would help better define the behavioral trends that we observed across meetings. We also did not directly explore the reasons why our participants exhibited certain information gathering behaviors during their meetings, and future work might explore such rationales to better understand the trends observed across teams in this study.

Another limitation of our study was the relative lack of diversity across our participants, with 83% identifying as male and 71% identifying as White. A more diverse group of participants might have adopted different information gathering approaches compared to what we observed in our data. Since our study investigated the approaches of a select sample of teams, more work is also needed to determine the extent to which our findings are transferrable to other novice engineering design contexts.

Furthermore, the stakeholders and domain experts from whom teams gathered information were diverse in terms of race, gender, and, in the case of project partners, occupation. However, we did not explore this diversity in depth. As such, some of these individuals may have possessed specific knowledge or background experiences that did not factor into our analysis, but that may have influenced how teams conducted their information gathering meetings.

Lastly, we did not evaluate the outcomes of team projects. There are many factors that influence design successes and failures, and a holistic accounting of these factors was outside the scope of this work. As such, we were unable to verify whether teams that exhibited information gathering behaviors that aligned more closely with recommended practices also developed more successful design solutions.

6.6.2 Implications

Engineering design education researchers may use our findings to broaden their understandings of how design expertise related to gathering information may develop. Our comparative analysis of information gathering meetings conducted by six novice teams identified two trends, a prioritization of domain expert perspectives and a preference for early and decisive meetings, that had not been described in depth by previous studies and that may be characteristic of novice designers. Our study further presented a list of recommended practices for conducting information gathering meetings – solicit diverse perspectives, use appropriate information gathering techniques, and conduct multiple meetings over time – that may also be used to evaluate design expertise related to gathering information. Future studies can explore the extent to which more experienced designers exhibit the recommended practices that we have identified and/or consider how decisions related to these practices are interconnected.

Design practitioners can also use our list of recommended practices introduced in Section 2 to reflect on their own information gathering approaches. Although our work draws upon previous literature, we have not found another resource that concisely identifies soliciting diverse perspectives, using appropriate information gathering techniques, and conducting multiple meetings over time as recommended practices. Our background discussion also uniquely highlights the ways that these three recommended practices may relate to one another. Our list and discussion of recommended practices may thus assist designers in planning effective information gathering meetings that align with recommended practices and could also support designers' reflection-in-action, i.e., reflection on design activities that occurs while designers are conducting these activities (Schön, 1983). For example, our list of recommended practices may help designers identify and subsequently address gaps in ongoing information gathering activities.

Lastly, our findings suggest that novice designers would benefit from additional support related to setting explicit information goals and conducting beneficial information gathering meetings throughout their design processes. Part of this support could involve training to assist novice designers with identifying co-creative design roles for their stakeholders to facilitate information gathering; training materials could be based on case studies such as those presented by Coleman et al. (2016) and Luck (2018). Design instructors might also leverage pedagogical tools such as the "Prototype for X" framework by Menold et al. (2019), which has been shown to support novice designers in engaging stakeholders throughout their design projects. Furthermore, novice designers working in capstone design contexts may struggle to solicit diverse stakeholder perspectives and/or navigate conflicts between these perspectives. As suggested by the case of Team C, one potential solution may be for novice designers in capstone contexts to meet with multiple stakeholders during each information gathering meeting. Future training might thus support novice designers in effective methods for gathering information in focus group or participatory design workshop settings.

6.7 Conclusion

Our study explored novice engineering design team approaches to conducting information gathering meetings in three ways: the types of individuals from whom teams gathered information, the timing of their meetings, and the information gathering behaviors exhibited by teams during their meetings. Teams employed a range of behaviors that were more similar to recommended practices, especially during their early meetings. Most teams also exhibited relatively few occurrences of information gathering behaviors that were less similar to recommended practices during their meetings, although it is important to note that even scarce occurrences of these latter behaviors can significantly impact stakeholder or domain expert responses. Furthermore, our findings revealed two key trends across team approaches that represented opportunities for improvement and may be characteristic of how novice designers conduct information gathering meetings. First, teams seemed to prioritize domain expert perspectives, employing deep exploratory information gathering techniques during domain expert meetings and reaching out to additional domain experts to inform their projects. While most teams also met with project partners, their partner meetings contained few instances of deep exploratory behaviors compared to domain expert meetings. In addition, teams preferred to conduct early and decisive information gathering meetings. Teams conducted most of their meetings during the early stages of their design projects and, based on the information gathering behaviors exhibited during these meetings, mainly used early meetings to establish problem definitions and choose final solution concepts. Teams then conducted few meetings during later design phases. Both trends diverge from recommended practices for conducting information gathering meetings. However, we did observe one team, Team C, who followed recommended practices in their approach by soliciting diverse stakeholder perspectives consistently over their project and by employing appropriate information gathering techniques during their meetings. The in-depth descriptions of novice approaches presented in this paper can be used to develop tools and pedagogy that support novice designers in conducting effective information gathering meetings. Design practitioners may also use our list of recommended meeting practices to reflect on their approaches and to gather more comprehensive information about stakeholder needs and requirements.

6.8 References

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Chapter 7 Discussion, Implications, and Future Work

7.1 Chapter summaries

As described in Chapter 1, the overarching goals of this dissertation were to: 1) deepen understandings of how engineering students and practitioners may engage with sociotechnical aspects of engineering work and 2) identify aspects of engineering students' and practitioners' perspectives and approaches that may be transferrable to other engineering contexts. In Chapters 2 and 3, we investigated how engineering students and practitioners conceptualized sociotechnical aspects of engineering work based on their previous experiences. In Chapters 4-6, we investigated how engineering students in co-curricular (Chapter 4) and capstone (Chapters 5-6) design contexts engaged stakeholders to inform their design projects.

7.1.1 Chapter 2 summary

Chapter 2 described a conceptualization of engineering as a sociotechnical discipline comprised of eight statements about engineering work that were synthesized from literature. These statements included "Engineering is a technical discipline," "Engineering is a social discipline," "Engineering is a team discipline," "Engineering is a global discipline," "Engineering makes the world a better place," "Engineering is a creative discipline," "Engineering is constantly evolving," and "Engineering is about synthesizing and integrating knowledge." Using these eight statements, we interviewed 28 engineering practitioners from various industries and with experience levels ranging from a few months to over 25 years. We asked participants to select two statements that aligned well with their engineering experiences and to describe a story from their experiences related to each statement that they selected. We also asked participants to select two statements that aligned less well with their experiences, and to provide their justification. In addition to recording participants' selections, we also analyzed participants' responses to identify their beliefs about engineering work.

Two statements were selected by more than ten participants as aligning *most* with their experiences: "Engineering is a team discipline (15/28 participants) and "Engineering is about synthesizing and integrating knowledge" (12/28 participants). These two statements were closely related to the beliefs about engineering work that were most frequently discussed by participants. Twenty-five out of 28 participants, in discussing their statement selections and engineering experiences, emphasized that engineering work is highly collaborative. Twenty-four out of 28 participants described the importance of technical knowledge for engineering work, and 23 out of 28 participants described the importance of communication skills for engineering work. While 22 out of 28 participants discussed societal implications of engineering work, these discussions were spread across a range of statements. For example, participants with international experiences selected the statement "Engineering is a global discipline" and discussed ways that they considered the broader societal and cultural contexts of international stakeholders. However, this statement was only selected by seven participants as aligning well with their experiences. One statement was selected by more than ten participants as aligning less well with their experiences: "Engineering is constantly evolving." The most frequent explanation provided by participants related to how the fundamental knowledge, tools, and processes that are required to perform engineering work do not change much over time.

7.1.2 Chapter 3 summary

Chapter 3 described a similar study as Chapter 2, but this time exploring the perspectives of engineering students. Thirty junior and senior-level undergraduate engineering students participated in this study. As in Chapter 2, participants were provided with the eight statements about engineering work and were asked to select two statements that aligned with their experiences and two statements that did not align. We recorded participants' selections and analyzed their responses to identify their beliefs about engineering work.

Similar to the practitioners in Chapter 2, "Engineering is a team discipline" (17/30 participants) and "Engineering is about synthesizing and integrating knowledge" (15/30 participants) were selected most frequently by student participants as aligning with their engineering experiences. Participants in this study also highlighted communication and collaboration as core parts of engineering work. However, different from practitioners, 15 out of 30 student participants selected the statement "Engineering is a social discipline" as aligning less well with their experiences. Participants mainly interpreted "social" in this statement in terms of interpersonal interactions and "social" bonding. Thus, in justifying their selections, participants indicated that while engineering is collaborative, it is not necessary "social," i.e., building friendships with teammates is not important for collaborating effectively. Discussions of other "social" aspects of engineering, such as societal impacts, were relatively limited.

7.1.3 Chapter 4 summary

Chapter 4 described an investigation into the needs assessment practices of a 12-member co-curricular design team. This team was conducting a needs assessment in a rural South American community in order to identify design problems that might motivate new design projects. Prior to engaging in field work in their partner community, team members completed trainings through the University of Michigan's Center for Socially Engaged Design (C-SED) on conducting needs assessments, writing needs statements, and gathering observational data. We conducted three rounds of interviews with participants: 1) prior to completing C-SED trainings, 2) after completing C-SED trainings, and 3) after completing field work. We analyzed these data to identify how participants' conceptions of recommended practices for conducting needs assessments developed through their training and field work. Participants' conceptions were compared to a list of recommended needs assessment practices that we synthesized from literature. As part of our analysis, we also identified challenges that affected the team's needs assessment process.

Participants described several practices for conducting needs assessments that aligned with recommended practices from literature. For example, every participant described the importance of consulting a wide range of stakeholders due to differences in stakeholder perspectives and identities ("account for diverse perspectives"). Participants also consistently described the importance of building local partnerships ("leverage local connections") and comparing different team members' perspectives and interpretations of stakeholder data ("compare data across the team"). However, participants described few practices related to collecting many types of data, deliberately choosing data collection methods, and developing rigorous metrics to evaluate identified needs. Participants also encountered challenges related to building a deep understanding of the local community context ("understanding the context"), optimizing their short time in the community ("optimizing short time in community"), and accessing certain stakeholder groups ("accessing stakeholders"). These challenges are likely transferable to other student co-curricular projects and represent specific barriers that other teams should account for as part of their needs assessment processes.

7.1.4 Chapter 5 summary

In Chapter 5, we explored how undergraduate engineering students in a mechanical engineering capstone design course interacted with stakeholders and domain experts during meetings that these teams conducted to inform their projects. Capstone design courses represent an important context of study because 1) they represent a culminating educational experience in which students apply knowledge accumulated across their undergraduate education and 2) a core goal of such courses is to prepare engineering students to enter professional practice. Thus, the ways that students approach their capstone design projects is often indicative of how they may approach similar engineering tasks during the early years of their professional careers. Six teams participated in this study and recorded meetings that they conducted with stakeholders and domain experts as part of their capstone course. Participants submitted 19 meetings in total. We analyzed these meetings to identify specific behaviors that students exhibited during their meetings.

Our findings included 22 distinct behaviors that participating teams exhibited during their meetings with stakeholders and domain experts. Eleven of these behaviors aligned well with recommended practices for stakeholder engagement from the literature, while the other eleven behaviors did not align well with recommended practices. We also identified three categories of behaviors. *Structural* behaviors included ways that participants sought to organize their meetings and clarify basic information. *Exploratory* behaviors included ways that students sought to elicit deep insights related to stakeholder or domain expert perspectives and experiences. *Collaborative* behaviors included ways that participants sought to support the participation of diverse stakeholders and domain experts within their design processes.

7.1.5 Chapter 6 summary

Chapter 6 built upon the findings described in Chapter 5 and explored additional data gathered from each team. The goal of this chapter was to investigate participating teams' stakeholder engagement approaches across meetings and to compare the approaches adopted by different teams. Thus, in addition to the meeting recordings submitted by teams, this chapter leveraged additional data, including interviews that we conducted with each team over the semester. Teams also submitted a list of all information gathering meetings that they conducted over the semester, along with a list of the individuals present at each meeting. We analyzed these data to identify when (i.e., during which design phases) teams engaged with stakeholders to inform their projects and the types of individuals with whom teams met. We also analyzed the frequency with which the information gathering behaviors identified in Chapter 5 occurred across submitted meeting recordings.

We identified two main trends across teams. These two trends had not been described in depth in previous literature and were potentially characteristic of how beginner designers approach stakeholder engagement activities. First, teams seemed to prioritize domain experts as sources of information. Teams employed *exploratory* behaviors that aligned with recommended practices most frequently during meetings where domain experts were also present. Several teams also met with domain experts who lacked a clear affiliation with the capstone course. In comparison, meetings involving project partners such as sponsors contained fewer *exploratory* behaviors, and teams mainly met with the project partners and users that were explicitly provided by the capstone course. In addition, we found that teams seemed to prefer early and decisive information gathering meetings. Twenty of the 36 meetings conducted by the six participating teams occurred during the first two (out of five) design phases. These early meetings also included frequent instances of information gathering behaviors related to clarifying information and verifying conclusions. Although these trends applied generally across teams, there was one participating team (Team C) that met with a range of stakeholders and conducted meetings consistently throughout their projects. This team seemed highly inclined to value stakeholder perspectives and was also placed in a favorable project context where multiple stakeholder perspectives were readily available. These factors may have facilitated Team C's utilization of a more advanced stakeholder engagement approach.

7.2 Synthesis of findings across chapters

7.2.1 Engineering student and practitioner conceptions of engineering work (Chapters 2 and 3)

This dissertation explored how engineering students and practitioners conceptualized engineering work based on their previous engineering experiences. Prior studies have identified various aspects of professional engineering practice, including that engineering practice involves cross-disciplinary communication and exchange (Anderson et al., 2010; Jesiek et al., 2019, 2021; Trevelyan, 2010), transcends geographic boundaries (Jesiek et al., 2021; Wong, 2021), impacts broader societal systems (Bijker, 1995; Kroes et al., 2006; Valkenburg, 2021), and is influenced by engineers' personal and social identities (Fila et al., 2014; McGee, 2020; Riley, 2017). However, few prior studies had directly explored the extent to which engineering students and practitioners recognize and attend to multiple and diverse sociotechnical aspects of engineering in their work. Furthermore, few studies had compared student and practitioner perspectives in depth to identify key similarities and differences in how engineering students and practitioners may conceptualize engineering work.

This dissertation developed a novel methodological approach to explore engineers' perspectives of engineering work. This approach involved eight statements, synthesized from literature, that described various aspects of modern engineering work. Since this is primarily an exploratory work, it is not possible to establish causality within our findings. However, there were several trends that emerged across our data that together deepen understandings of how engineering students and practitioners may conceptualize engineering work. These trends are important due to how they expand upon prior literature and/or reveal previously un(der)reported aspects of how engineering students and practitioners may conceptualize engineering work. These trends may be transferrable to other engineering settings and thus deserve further study.

In describing their previous engineering experiences, our engineering student and practitioner participants both discussed their collaborations with other engineers substantially more than they discussed other sociotechnical aspects of engineering work. Both students and practitioners consistently highlighted collaboration and communication as core aspects of engineering practice. This finding aligns with prior literature that has similarly described collaboration as a core aspect of engineering education and practice (Anderson et al., 2010; Jesiek et al., 2019, 2021; Passow & Passow, 2017; Trevelyan, 2010). However, the goal of our study was to understand the extent to which our participants recognized multiple and diverse sociotechnical aspects of engineering work. Through this lens, it was notable that over half of our student and practitioner participants selected the statement “Engineering is a team discipline” as aligning most with their experiences, despite having eight different statements about engineering work to choose between. The frequency with which our participants selected “Engineering is a team discipline” over other statements indicates that the collaborative aspects of engineering practice were highly salient for many of our participants, more so than other sociotechnical aspects of engineering practice. This finding represents a novel insight related to how engineering students and practitioners may conceptualize engineering work. More research is needed to explore this finding in greater depth, for example to determine reasons why collaborative aspects of engineering work may be more salient for engineering students and practitioners compared to other sociotechnical aspects of engineering work.

Our engineering student participants' conceptions of engineering as a social discipline may have been limited. Ultimately, we have limited direct evidence of how engineering students in our study conceptualized the broader societal aspects of engineering work. In part, this was because our engineering student participants discussed their collaborations with other engineers to a much greater extent than they discussed other sociotechnical aspects of engineering work. For example, in addition to frequently choosing "Engineering is a team discipline" as a statement that aligned closely with their experiences, half of our engineering student participants indicated that the statement "Engineering is a social discipline" did *not* align with their experiences. In justifying their statement selections, many of our engineering student participants referred to how "social" interactions, such as bonding with teammates, were not important to effective teamwork in engineering classrooms. Thus, our engineering student participants primarily interpreted the statement "Engineering is a social discipline" as referring to interpersonal interactions between engineers, rather than other sociotechnical aspects of engineering work such as societal impacts. This was a novel finding, and more research is needed to understand why engineering students might interpret "social" as referring to interpersonal interactions between engineers rather than other sociotechnical aspects of engineering work.

Although the reasons why our student participants consistently interpreted "social" as referring to interpersonal interactions are unclear, there are a few possible explanations. For example, our student participants may have been unused to using the word "social" to describe societal impacts, perhaps due to curricular gaps. Our student participants generally discussed the importance of considering societal implications and stakeholders in their engineering work, but these discussions were not strongly connected to any particular statement. In other words, our student participants did not strongly associate the societal implications of engineering work with the statement “Engineering is a social discipline.”

Alternatively, our student participants may have interpreted “Engineering is a social discipline” as referring mainly to interpersonal interactions because they felt that other of our eight statements more directly encompassed the societal impacts of engineering work. For instance, both engineering students and engineering practitioners used the statement “Engineering makes the world a better place” to comment on whether engineering does in fact make the world a better place, typically because they felt that this statement aligned poorly with their experiences. However, this statement was selected by fewer than half of our participants overall. Another statement that engineering practitioners, but not engineering students, used to discuss the societal implications of engineering work was “Engineering is a global discipline.” However, this statement was only selected by seven practitioners overall as aligning with their experiences, most of whom referenced direct experiences considering international markets or collaborating with international engineers. Our engineering student participants generally lacked these international experiences, which is partially why our student participants rarely selected the statement “Engineering is a global discipline” to discuss.

In part, our challenge with determining specific reasons that engineering students interpreted “Engineering is a social discipline” as mainly referring to interpersonal interactions stems from the fact that our practitioner participants rarely selected this statement. Only nine practitioners selected this statement overall (two align, seven not align), meaning that it is difficult to draw inferences as to how our practitioner participants were interpreting this statement. Understanding how engineering students and practitioners may interpret the word "social" as applied to engineering, and the reasons behind these interpretations, is thus a topic for future work.

Our engineering student and practitioner participants conceptualized engineering collaborations in substantially different ways based on their different experiences. Since both engineering students and engineering practitioners in our study discussed collaborative aspects of engineering work in depth, we were able to identify similarities and differences in how our participants conceptualized their collaborations. Engineering practitioners, but not students, emphasized how modern engineering work is often cross-disciplinary and requires engineers to leverage cross-disciplinary communication skills. Engineering students did not describe similar conceptions of engineering work. Instead, engineering students often framed collaborations in terms of increased productivity or the benefits of consulting diverse perspectives (i.e., based on diverse background experiences). Furthermore, engineering students indicated that more "social" aspects of their collaborations, such as building relationships with teammates, were not necessary for effective collaborative work, especially in curricular engineering environments. Engineering practitioners did not describe similar perspectives. These potential differences between student and practitioner perspectives on collaborative engineering activities have not been described in prior engineering work and deserve further study.

Ultimately, it is unclear why engineering students and practitioners described collaborative aspects of engineering work differently. Given the design of the studies described in Chapters 2 and 3, the most likely explanation is that engineering students and practitioners have qualitatively different experiences with engineering teams. These differences may include a variety of factors, including differences in how student and professional engineering teams are constructed, the types of work performed by student and professional engineering teams, or the dominant cultures of engineering educational environments compared to work environments. These differences should be explored in greater depth in future work.

Furthermore, our finding that engineering students viewed relationship-building with teammates as unnecessary to engineering collaborations has not been described in depth in prior literature. Ultimately, we did not explore students' perspectives in sufficient depth to identify specific reasons why students consistently described their collaborative activities in this way, other than that students' educational environments seemed to play a role. As described in Chapter 3, it is possible that this perspective represents an instance of the *technical-social dualism*, which has been previously described in literature as a cultural norm that leads engineers to view technical aspects of engineering work as separate from, and more important than, more social aspects of engineering such as interpersonal interactions between engineers and/or consideration of broader societal impacts (Cech, 2014; Faulkner, 2000; Niles, Roudbari, et al., 2020; Riley, 2017). However, the *technical-social dualism* has not been described in this specific way before (i.e., in terms of separating out more "social" activities from engineering collaborations), so further study is needed to understand this potential connection more fully. More research is also needed to identify specific reasons that engineering students may view relationship building as unnecessary for effective collaborations within their engineering courses, and to determine how this perspective may influence engineering students' approaches to their engineering work.

Our engineering practitioner participants discussed technical aspects of engineering work in depth, but mostly in the context of collaborations with other engineers. Given the influence of the technical-social dualism as a cultural norm in engineering (particularly as originally described by Faulkner (2000)), we expected many of our participants to select the statement “Engineering is a technical discipline” as a statement that aligned well with their experiences. This did not happen – neither engineering students nor engineering practitioners consistently selected the statement “Engineering is a technical discipline” as aligning well with their experiences. However, engineering practitioners still discussed technical aspects of engineering work consistently overall, mainly related to the statements “Engineering is a team discipline” and “Engineering is about synthesizing and integrating knowledge.” Many of these discussions of technical aspects of engineering work related to practitioners’ other discussions of communication and collaboration in engineering work. Thus, similar to prior work by Anderson et al. (2010) exploring the perspectives of engineering practitioners, we found that practitioner participants in our study seemed to consider their technical engineering work to be closely intertwined with, and generally inseparable from, collaborative aspects of engineering. We have not yet analyzed our student participants’ perspectives on technical aspects of engineering work in sufficient depth to provide a direct comparison.

It is ultimately unclear whether the perspectives of our practitioner participants represent a substantial divergence from the technical-social dualism in engineering. For example, other literature (e.g., Cech, 2014; Niles, Contreras, et al., 2020; Niles, Roudbari, et al., 2020) has described versions of the technical-social dualism that equate “social” with broader societal considerations, rather than just interpersonal factors as in Faulkner (2000). The ways in which our practitioner participants connected their technical engineering knowledge to broader societal considerations was not generally clear from our data, although company or product contexts (e.g., international work vs domestic work) seemed to play a significant role in whether our practitioner participants had opportunities to make such connections. It is possible that, in contemporary engineering work, the technical-social dualism now mainly operates in terms of elevating technical engineering work over the consideration of societal impacts of this work. Alternatively, it is possible that there are aspects of how engineering practitioners conceptualize their collaborative activities that align with the technical-social dualism and that were not revealed by our study. More research is needed to explore these possibilities in depth.

7.2.2 Engineering students' approaches to stakeholder engagement in curricular and co-curricular contexts (Chapters 4-6)

This dissertation also explored how engineering students engaged with stakeholders to inform curricular and co-curricular projects. We explored engineering students' approaches to stakeholder engagement in two contexts: a needs assessment in a rural South American community and a mechanical engineering capstone design course. Despite differences in project contexts, there are a few points of comparison that are worth highlighting due to their implications for engineering design research and pedagogies.

Engineering students employed approaches that resembled recommended stakeholder engagement practices in both the needs assessment context (Chapter 4) and the mechanical engineering capstone context (Chapters 5-6). In Chapters 5 and 6, our analysis of teams' information gathering meetings with stakeholders revealed 11 information gathering behaviors that aligned with recommended practices. These behaviors included ways that participants structured their meetings, explored stakeholders' perspectives in depth, and supported stakeholders' participation in their design processes. Students' use of recommended practices for stakeholder engagement in capstone contexts had not previously been described in depth. Thus, the work in this dissertation deepens understandings of how engineering students in capstone courses may interact with stakeholders to inform their design projects.

As part of deepening understandings of student approaches to stakeholder engagement, the work in this dissertation uniquely highlighted how capstone teams may employ *collaborative* behaviors in their interactions with stakeholders. *Collaborative* behaviors supported stakeholders' understanding of and participation in capstone teams' design tasks. Prior work (e.g., Mohedas, 2016; Mohedas, Daly, Sienko, et al., 2016) has mainly focused on the need for capstone teams to develop skills related to asking open-ended questions and exploring stakeholders perspectives in depth (which we defined as *exploratory* behaviors in this dissertation). Almost all meetings between capstone teams and stakeholders that were analyzed as part of this dissertation included instances of both *collaborative* and *exploratory* behaviors. Our work thus highlights the range of ways that capstone teams may engage with stakeholders during information gathering meetings, as well as the range of knowledge that capstone teams may need to conduct these meetings successfully.

In Chapter 4, we did not gather direct data on the needs assessment team's practices during their field work experience. However, the needs assessment team consistently described in post-field work interviews three practices that they utilized to make their needs assessment successful. These practices included "account for diverse stakeholder perspectives," "leverage local connections," and "compare stakeholder data across the team," and all three practices resembled recommended literature practices. This was a novel research finding since prior studies had not described engineering students' perspectives on needs assessment practices in depth. Participants in our study described learning these practices through a combination of their pre-field work training and their field work experiences. More research is needed to determine what elements of these training and field work experiences may have contributed most to our participants learning these recommended practices. In addition, our evidence of participants' usage of these recommended practices is based on retrospective interviews. More data is needed to determine how engineering students may employ these practices during their field work experiences and to identify other recommended practices that engineering students could be employing as well.

In both the needs assessment context and the mechanical engineering capstone context, engineering students' abilities to employ recommended practices seemed to be affected by project contexts. This trend was most obvious in Chapter 4, since we directly asked participants to describe challenges that they encountered as part of their needs assessment experience. Participants consistently cited "understanding the community context," "optimizing short time in the community," and "accessing stakeholders" as challenges that affected their needs assessment process. For example, the challenges "optimizing short time in the community" and "accessing stakeholders" made it more difficult for the team to "account for diverse stakeholder perspectives." These challenges have not been described in depth in prior work but are likely transferable to similar design project contexts.

Contextual constraints also seemed to impact how the capstone teams in Chapters 5 and 6 approached their stakeholder engagement activities, although we do not have data to make firm conclusions. In Chapter 6, we found that capstone teams seemed to prefer early and decisive meetings. This observed trend was based on two aspects of our data. First, most meetings conducted by teams occurred during teams' first two design stages. Second, teams employed behaviors such as *verify the conclusions drawn from meetings* and *avoid misinterpretations* most often in their early-stage stakeholder meetings, but less so in later-stage meetings. The observation of this trend was a novel finding from our studies – thus, the reasons why teams preferred early and decisive information gathering meetings were unclear. One plausible explanation stems from our conceptual framework related to beginner and advanced designer behaviors, since limited problem exploration and lack of iteration have been previously described as characteristic beginner approaches (Atman et al., 2007; Crismond & Adams, 2012). Another likely explanation, pending further study, relates to the capstone course context. The capstone course was only a single semester and required students to move quickly through several design stages to develop a working prototype. Teams produced design reports, which were graded, at the end of each design stage. Although the capstone instructors recommend to students that they meet with stakeholders consistently throughout their projects, the grading criteria of later design reports were more focused on engineering analyses and design validation. Due to the short duration of the capstone course, teams may have felt that they did not have time to conduct additional stakeholder meetings in later design stages given that such meetings would not obviously contribute to their course grade.

In Chapters 5 and 6, we also found tentative evidence that capstone project contexts can in some ways positively influence how engineering students engage stakeholders. For example, Team C in these studies was able to meet with their user and several different project partners simultaneously due to their project context. Team C, compared to other participating teams, also met with their stakeholders consistently throughout their project and leveraged the *collaborative* behavior *develop mutual understanding with the stakeholder or domain expert* more than seven times per meeting. Thus, Team C was unique in that they employed recommended practices (both within meetings and across meetings) for engaging stakeholders to a greater extent than other teams in our study. This finding was notable given that Team C had roughly the same amount of prior experience with stakeholder engagement compared to other teams in our study, thus suggesting that factors other than experience were also influencing Team C's approach. Our data do not enable us to establish a causal relationship between project context and Team C's approach – and prior studies of capstone courses have not described engineering students' approaches in sufficient depth to provide additional clarification regarding this potential relationship. However, it seems likely based on our comparison of Team C with other teams in our study that project context, and specifically the regular availability of multiple stakeholders, did to some extent positively influence Team C's approach to stakeholder engagement. More work is needed to understand in greater depth how capstone course contexts may influence engineering students' approaches to stakeholder engagement, both positively and negatively, independent of students' understanding of recommended stakeholder engagement practices and/or experience level.

In the needs assessment context, participants struggled to employ a variety of data collection methods strategically and analyze their stakeholder data effectively. While participants in Chapter 4 described recommended practices related to consulting diverse stakeholder perspectives and leveraging local connections, participants also described few practices related to gathering many different types of stakeholder data (e.g., both interview and observational data) and systematically analyzing their data. These findings were novel in the sense that few prior studies have explicitly described how engineering students may struggle with gathering and analyzing stakeholder data in the context of community-engaged, co-curricular projects. These findings also resemble prior observations of engineering students in other design contexts. For example, Sugar (2001), in a study involving graduate student software designers, previously observed that student designers may conduct stakeholder meetings but subsequently struggle to apply information from these meetings to inform their design decisions. In addition, Mohedas et al. (2014) found that student teams in a mechanical engineering capstone course struggled to gather information from stakeholders that they felt was directly relevant to the development of user requirements. Our findings seem to reflect similar themes in a different design context, i.e., our participants in Chapter 4 gathered stakeholder data but may have been unclear how best to use this data to inform their design project and may have struggled to gather data that was directly relevant to their project. These findings are important given how challenges with gathering and analyzing stakeholder data during early-stage design activities in community-engaged settings can lead to later project failures (Lucena et al., 2010; Nieusma & Riley, 2010; Wood & Mattson, 2016). More work is needed to determine whether our findings are transferrable to other student-led community-engaged projects.

7.2.3 Findings that bridge the two halves of the dissertation

Our conceptual framework of engineering cultural characteristics from Chapters 2-3 has some overlap with the studies discussed in Chapters 4-6. In this subsection, we apply our engineering cultural characteristics framework to interpret our findings from Chapters 4-6.

The prioritization of domain expert perspectives by capstone teams that we observed in Chapter 6 aligns with the technical-social dualism in engineering. Teams employed *exploratory* behaviors to explore domain experts' perspectives and knowledge in depth but did not explore project partners' perspectives in similar depth. Ultimately, we do not know why capstone teams in Chapter 6 prioritized domain expert perspectives and whether the technical-social dualism played a role. However, the differences in how our participants approached domain expert and project partner meetings were similar to the prioritization of technical knowledge that is characteristic of the technical-social dualism (Cech, 2014;

Khosronejad et al., 2021; Niles, Contreras, et al., 2020; Niles, Roudbari, et al., 2020). Niles et al. (2020), in a study of engineering students experiences with public welfare engagement in two different engineering programs, has shown how the technical-social dualism may impact engineering students' stakeholder engagement approaches in educational design contexts other than capstone. More work is needed to understand specific ways that the technical-social dualism may influence student teams' approaches in capstone contexts as well, to provide greater clarity to our findings.

7.3 Limitations

Limitations have been discussed with regards to each individual chapter. However, there are three limitations that apply across studies that are important to reiterate.

First, we sought to gather detailed descriptions of how engineering students and practitioners conceptualized and engaged with sociotechnical aspects of engineering work. Our goal was to leverage this deep detail to identify aspects of our participants' conceptions and approaches that may be transferrable to other engineering contexts. However, there are likely other ways that engineers may conceptualize or approach sociotechnical aspects of their engineering work that were not described in this dissertation. For example, many of our practitioner participants in Chapter 2 worked in large-scale, corporate industries. Practitioners at smaller companies or start-ups might conceptualize the sociotechnical aspects of engineering work differently. Similarly, many of our engineering student participants in Chapter 3, and all our participants in Chapters 5 and 6, were studying mechanical engineering. The conceptions and practices described in these Chapters thus may be most indicative of how mechanical engineers think about and approach sociotechnical aspects of engineering. Further work is needed to identify how conceptions and practices may vary across engineering disciplines.

A second limitation is that engineering student approaches to activities such as stakeholder engagement may vary substantially across different engineering project contexts. Even students in the same project context, such as a recurring capstone course, may exhibit different approaches in different semesters of the course. Thus, our findings in this dissertation are not meant to be indicative of how engineering students approach sociotechnical aspects of engineering work in all curricular or co-curricular contexts. Rather, our goal was to highlight elements of our participants' conceptions, approaches, and experiences that could also emerge in other contexts and that instructors might use to guide pedagogical decisions.

A third limitation was that many of the participants in this dissertation identified racially as White (18/28 participants in Chapter 2, 18/30 participants in Chapter 3, 5/12 participants in Chapter 4, and 17/24 participants in Chapters 5 and 6). Thus, our findings may not reflect how engineers with other racial identities conceptualize sociotechnical aspects of their engineering work and engage with stakeholders. For example, related to our work in Chapters 2 and 3, literature suggests that engineers of color possess unique ways of conceptualizing sociotechnical aspects of engineering work that are grounded in their cultural values (Carlone & Johnson, 2007; McGee, 2020; Winchester, III, 2019). Future work might explore in greater depth the relationship between engineers' social identities and the ways that they conceptualize and approach sociotechnical aspects of their work.

7.4 Implications across chapters

Implications have previously been described with regards to each individual chapter. Below, we describe implications for engineering education, practice, and research that were relevant across chapters.

7.4.1 Implications for engineering education

Engineering instructors should highlight the diverse ways that engineering is a sociotechnical discipline. Our student participants in Chapter 3 mainly interpreted our statement "Engineering is a social discipline" as referring to interpersonal interactions between engineers. In addition, discussions of how engineers should consider stakeholders and societal impacts occurred generally across student participants but were not connected to specific statements. These findings could indicate a limited understanding of the diverse ways that engineering is a sociotechnical discipline, including the ways that engineering impacts society and the ways that engineers may engage stakeholders to inform their work. Engineering instructors could make these sociotechnical aspects of engineering more salient for students by explicitly discussing ways that engineering is a sociotechnical discipline within their course materials. For example, in introductory engineering design courses, instructors might highlight how the design decisions made by engineers impact society. Instructors might also describe how engineers learn about the societal contexts of their work through stakeholder engagement activities and/or secondary research. In a more advanced mechanical engineering course, such as thermodynamics or fluids, instructors might provide examples of how the content of the course is applied in the real world, with reference to specific technologies. Instructors in these courses might also highlight how their course content intersects with other content or disciplines (both in engineering and the humanities) to demonstrate how modern engineering work requires the contributions of diverse professionals with wide-ranging expertise.

In addition to these changes to course content, instructors could further support engineering students' learning through research and design projects that provide opportunities for students to engage stakeholders and analyze the societal implications of engineering work. As one example, instructors in a class related to sustainability and/or energy sources could assign students to explore, in teams, the implications of different types of near-future energy technologies for their local communities. Students might identify stakeholders who are likely to benefit most from these near-future technologies, as well as stakeholders who may be harmed by these technologies. Projects such as these would provide opportunities for students to practice engaging with sociotechnical aspects of their work, since research shows that opportunities for practice are important for supporting students' learning (Dym et al., 2005; Kolb, 1984).

Engineering instructors should teach engineering students how to employ both *exploratory* and *collaborative* behaviors to solicit stakeholder perspectives. Our participants in Chapters 5 and 6 relied on a variety of behaviors to solicit and understand stakeholder perspectives as part of their capstone course. Our participants also exhibited several instances of *exploratory* and *collaborative* behaviors that were less similar to recommended practices, and these behaviors represent specific knowledge gaps that might be addressed through instruction. In the context of capstone courses, instructors might add course content related to soliciting stakeholder perspectives in depth and also content related to building mutual understanding with stakeholders and supporting stakeholders' participation in design projects. For example, capstone instructors might leverage case studies that demonstrate various ways that engineers might support stakeholders' participation. These case studies could be drawn from existing participatory design examples such as Luck (2018). Instructors might also use our comparison of capstone teams in Loweth et al. (2019) as another case study example to demonstrate both effective and ineffective ways to support stakeholders' participation and solicit stakeholder perspectives.

However, engineering students engage stakeholders in a variety of project contexts, not just capstone. For instance, the needs assessment team in Chapter 4 would likely have benefited from instruction on both *exploratory* and *collaborative* approaches to soliciting stakeholder perspectives, given the importance that this team placed on accounting for diverse stakeholder perspectives. Thus, ideally engineering students would be exposed to content on *exploratory* and *collaborative* approaches to soliciting stakeholder perspectives prior to capstone, which typically occurs during the last year of undergraduate engineering curricula. One possibility would be to include this content in introductory engineering courses, particularly those that include a significant design or stakeholder engagement component. Another possibility would be to provide resources related to stakeholder engagement, such as the learning blocks described by Young et al. (2017) and Strehl et al. (Accepted), that are independent of specific courses and that students might leverage to support their co-curricular projects. These learning blocks include descriptions of recommended practices, knowledge checks to gauge student understanding, and application tasks that provide students opportunities to practice soliciting information from stakeholders; research suggests that these blocks are effective for supporting student learning (Strehl et al., Accepted; Young et al., 2017).

Engineering instructors could use our list of potential student information gathering behaviors that align and do not align with recommended practices (Table 5.5) as a reflection tool to support students' development of stakeholder engagement skills. This tool could be implemented as part of pedagogies that teach students how to use *exploratory* and *collaborative* behaviors to solicit stakeholder perspectives. To use the tool, students could record themselves conducting information gathering meetings with stakeholders, and then review transcriptions of these recordings to identify how often they employed behaviors that aligned or did not align with recommended practices. Students might also use this tool to plan their stakeholder meetings. For example, students might prepare an interview protocol for a stakeholder meeting, and then use Table 5.5 to identify strengths of their protocol, opportunities to improve their questions or meeting structure, and opportunities to apply a wider range of information gathering behaviors to solicit stakeholder perspectives.

Engineering instructors should teach engineering students how to gather and analyze several different types of stakeholder data. Based on our findings in Chapter 4, engineering students would benefit from instruction related to specific methods for analyzing stakeholder data and translating this data into needs statements (or other design deliverables such as user requirements). In addition, capstone teams in Chapter 6 seemed to struggle to identify specific information goals for stakeholder meetings compared to domain expert meetings. Thus, instructors in capstone courses and other courses with substantial stakeholder involvement might add course content that describes how to identify specific information goals for stakeholder meetings and align data collection methods with information goals. The “prototyping canvas” developed by Lauff et al. (2019) represents one example of how to structure this content for students. Within this canvas, designers start by identifying assumptions and questions that they have about their stakeholders and/or the technical feasibility of their potential solutions. They then identify which of these questions are the highest priority to answer and develop a specific plan to answer these questions using one or more prototyping strategies. Similarly, in a course such as capstone, instructors might start by having students identify key questions about their design projects. Instructors might then describe a range of data collection strategies (such as interviews, focus groups, observations, and surveys) and highlight the types of questions that each data collection strategy is best equipped to answer. Subsequently, instructors could assign students to develop specific data collection plans, including the stakeholders that might provide relevant data and the data collection strategies used, related to each of the key questions that students identified. After collecting data, instructors might guide students in identifying commonalities and differences across their stakeholder data that could be expanded upon through further data collection activities and/or that might inform design decisions.

As with our recommendation related to *exploratory* and *collaborative* approaches to soliciting stakeholder perspectives, engineering students would ideally be exposed to content on gathering and analyzing several different types of stakeholder data prior to capstone. Covering this content in introductory engineering courses or through additional resources such as learning blocks could be an option in this case as well.

Engineering instructors should intentionally structure stakeholder engagement opportunities to support students' stakeholder engagement approaches. Ultimately, the ways that engineering instructors structure stakeholder engagement opportunities depend heavily on educational and curricular contexts. However, based on our findings in Chapters 4-6, there are a few possible approaches that engineering instructors may adopt. These suggestions for changes to project structure would function in addition to lectures that discuss recommended practices for stakeholder engagement, as described earlier in this subsection. One suggestion would be that instructors, such as in capstone, deliberately scope and assign projects that involve three or more core stakeholders that are geographically situated close to the university and who are excited to engage with students. This project context resembles Team C's project context and may facilitate students in exploring diverse stakeholder perspectives in depth. Another suggestion would be to implement longer-duration design project opportunities to lessen the impacts of time constraints on students' stakeholder engagement processes. An example of a longer-duration learning opportunity would be a two-semester capstone course where the first semester is devoted to identifying relevant stakeholders, gathering information from these stakeholders, analyzing stakeholder data to identify needs statements and requirements, and exploring the broader social, cultural, political, environmental, and economic contexts of the design project. Then, after the project context has been thoroughly explored, engineering students might start applying their knowledge to develop appropriate solutions during the second semester.

7.4.2 Implications for engineering practice

Engineering practitioners should use our lists of recommended practices in Chapters 4-6 to guide their stakeholder engagement approaches. We concisely synthesized lists of recommended practices from literature for conducting community-based needs assessments and meeting with stakeholders to inform design projects. Collectively, these practices represent ways that engineering practitioners can include diverse stakeholder perspectives within their design processes, so that their design work effectively addresses genuine stakeholder needs. Engineering practitioners could use our lists of recommended practices in various ways. For example, practitioners might use our lists of recommended practices while developing their stakeholder engagement plans to make sure that they are consulting diverse stakeholders consistently throughout their work and employing a range of data collection methods strategically. Practitioners might also use our lists of recommended practices to reflect on their engineering work. For example, if problems arise during later stages of engineering work that seem related to inadequate problem-scoping or needs identification, practitioners might use our lists of recommended practices to identify ways that they could have engaged stakeholders more effectively. Through this reflection, practitioners might identify how they could change their stakeholder engagement approaches for future projects to better align with recommended practices.

7.4.3 Implications for engineering design and education research

Engineering design and education researchers should attend to the diverse ways that engineering is a sociotechnical discipline in their studies of engineering students and practitioners. Our work highlighted various ways that engineering is a sociotechnical discipline, including the societal impacts of engineering, collaborations between engineers, and engineers' stakeholder engagement activities. Ultimately, as described in Chapter 1, these various sociotechnical aspects of engineering work are all closely related and are influenced by engineers' social identities. To develop deeper understandings of how engineers engage with sociotechnical aspects of their work, it is important to investigate intersections between different sociotechnical aspects. For example, in future studies of how engineering students in capstone courses engage with stakeholders, researchers should also gather data on the internal dynamic between capstone team members as well as the ways that team members' identities and experiences influence their conceptions of stakeholder engagement activities. This data would allow researchers to identify more directly how engineering students' conceptions of collaborative aspects of engineering work (e.g., as described in Chapter 3) may impact other aspects of their engineering work. This data may also reveal additional reasons that capstone teams may adopt substantially different approaches to stakeholder engagement, as we found in Chapter 6. Similarly, in future studies of engineering practitioners, researchers should explicitly explore intersections between the societal impacts of engineering work and the ways that engineers collaborate in performing this work. This data would allow researchers to identify more directly how practitioners' approaches to engineering work align with or diverge from the *technical-social dualism* in engineering, as discussed in Section 7.2.1.

7.5 Future work

There are several opportunities to build upon the work described in this dissertation. For example, a series of studies might explore how engineering practitioners engage with stakeholders to inform their engineering work. These studies might gather practitioners' reflections on their stakeholder engagement practices, as well as recordings of practitioners' meetings with stakeholders, and analyze these data to determine the extent to which practitioners' approaches align with the recommended practices identified in Chapters 4-6. This type of study would deepen understandings of how expertise related to stakeholder engagement may be developed. These studies might also uncover additional practices that practitioners use to engage stakeholders that have not been described in prior literature.

Another opportunity for future work relates to the intersection between engineering cultures and how engineering students approach sociotechnical activities such as stakeholder engagement. Literature suggests that there is a close link between how engineering students are conditioned to think about sociotechnical aspects of engineering and how students approach sociotechnical aspects of their work in practice (Cech, 2014; Khosronejad et al., 2021; Niles, Contreras, et al., 2020; Niles, Roudbari, et al., 2020). However, more work is needed to understand this link in greater depth. For example, one study might explore how student teams in a capstone design course conceptualize sociotechnical aspects of their work. Interviews conducted throughout the semester would record participants' initial conceptions, as well as how their conceptions change over the capstone semester. The study would also gather data on each team's respective approaches to stakeholder engagement, similar to the data described in Chapter 6. The engagement approaches of teams with more advanced or comprehensive conceptualizations of the sociotechnical aspects of engineering work would be compared to the approaches of teams with less inclusive conceptions to determine potential differences.

A novel finding from this dissertation related to how engineering students and practitioners described collaborative aspects of engineering work in fundamentally different ways. Since this was primarily an exploratory study, the reasons behind these differences are unclear. Future research could explore differences in how engineering students and practitioners experience collaborative engineering work in greater depth. For example, future work might explore engineering educational environments to identify specific ways that these environments are influencing students' perceptions of collaborative aspects of engineering work. Future research might also explore the perceptions of engineering practitioners in a wider range of industries to understand how different work contexts influence practitioners' conceptions of engineering work.

Another potential area of future work relates to the evaluation of the pedagogical recommendations made in Section 7.4.1. As pedagogies that center sociotechnical aspects of engineering work continue to be developed and implemented, research might evaluate how these pedagogies impact students' learning and professional development. Potential research topics might include: the extent to which engineering pedagogies with an explicitly sociotechnical focus support students in adopting effective approaches to stakeholder engagement, the extent to which these pedagogies support students in developing more inclusive conceptions of engineering, the extent to which students see these pedagogies as relevant to their (future) professional practice, and the extent to which these pedagogies support students in identifying the impacts of broader societal systems when defining engineering design problems. Findings from this research could inform iterations of sociotechnical pedagogies to better support students in adopting effective sociotechnical approaches to their engineering work.

7.6 Conclusion

This dissertation explored how engineers conceptualized sociotechnical aspects of their engineering work and approached sociotechnical activities such as stakeholder engagement. In Chapters 2 and 3, we explored how engineering students and practitioners conceptualized engineering work based on their prior experiences. We found that engineering students and practitioners both highlighted their engineering collaborations more so than other sociotechnical aspects of engineering work. Engineering students and practitioners also understood the importance of collaboration differently. For example, engineering students, but not practitioners, indicated that effective collaborations did not require engineers to build close interpersonal relationships. In Chapters 4-6, we explored how engineering students engaged stakeholders in co-curricular and capstone settings. We found evidence of engineering students employing recommended stakeholder engagement practices in both settings. We also found that different aspects of project contexts, such as time constraints and availability of stakeholders, seemed to impact how students approached their stakeholder engagement activities. Based on our findings, we recommend that engineering instructors highlight the diverse ways that engineering is a sociotechnical discipline, teach students a range of approaches for engaging stakeholders, support students in gathering and analyzing multiple types of stakeholder data, and structure students' stakeholder engagement opportunities to encourage effective engagement approaches. We also recommend that engineering practitioners and students use our lists of recommended stakeholder engagement practices in Chapters 4-6 to guide their stakeholder engagement approaches. Lastly, we recommend that engineering design and education researchers attend to the diverse ways that engineering is a sociotechnical discipline in their studies of engineering students and practitioners to more fully understand how various sociotechnical aspects of engineering work are connected.

7.7 References

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