TEACHER TALK IN ENGINEERING DESIGN PROJECTS

by

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Dedicated to my mom, who showed me passion for teaching, and for dad, who showed me passion for engineering, among so many other things they have given me.

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ABSTRACT

Teacher talk is a major way in which instructors support and provide scaffolding for their students, frame their pedagogies, model ways of thinking, and convey ideas. Effective teacher talk about engineering design at all levels of students' educational experiences has the potential to better prepare students for success in engineering and increase the diversity of engineering fields. However, the most effective ways for teachers to talk to their students during engineering design are not well understood. This three-study dissertation examines the ways in which instructors use talk to interact with their students through a variety of different engineering design settings and contexts, with potential implications to improve and educate how teachers present engineering to their students. Overall, this thesis addresses the research question: How do instructors (teachers and professors) use talk interactions to scaffold students in engineering design? The first study is a case study that focuses on the whole class verbal interactions of an experienced and successful teacher throughout the entirety of a month-long life science-based STEM integration unit in a 6th grade classroom. Results show that this teacher's talk helped to integrate engineering with the science and mathematics content of the unit and modeled the practices of informed designers to help students learn engineering in the context of their science classroom. He framed lessons around problem scoping, incorporated engineering ideas into scientific verbal interactions and aligned individual lessons and the overall unit with the engineering design process. The second study uses naturalistic inquiry to examine how six different teachers of 6th, 7th, and 8th grades talked to their students while the students were actively working in small teams on engineering design projects. Results indicate that the teachers had conversations with the students about many areas of engineering, demonstrating that middle school teachers can have high-level conversations with their students about their design ideas. However, when students struggle to communicate their ideas, the different levels of support outlined in the coding framework and examples provide a structure of support for teachers to give their students. Additionally, there were many areas of engineering that were underemphasized in the teachers' talk and each teacher had different emphasis. The third study examines how professors in mechanical and biomedical engineering talk to their students during introductory engineering design projects. Results show that the three professors used their talk to support their role as a guide and mentor to students during their projects, although they had different goals with their mentoring. They used their talk to push

students' ideas to consider their problems more broadly, encouraged students to brainstorm diverse out-of-the-box ideas, supported teaming, and modeled engineering language. They maintained a focus on non-technical content, including the iterative nature of design, teaming, and communication, but made references to how students would apply this knowledge in future, more technical projects. The professors supported many challenges for novice designers, including supporting prototype development to represent ideas and iterating to improve their ideas, but were not comprehensive in their support of other challenges, especially problem scoping, testing and troubleshooting, and reflecting on the process. The final chapter of this dissertation presents a synthesis across the three studies and a summary of the implications for teaching. These implications include many examples of high-quality engineering conversations with students at different levels of their education, identification of aspects of engineering education that are underemphasized in teachers' talk to their students, and connections to needed areas of support and professional development for teachers.

1. OVERVIEW OF ALL THREE STUDIES

Engineering design involves complex processes that beginning designers are not often able to complete alone or with teams of peers. In order for students to authentically practice complex engineering design problems, teachers must provide scaffolding to support their students' learning. A major way in which instructors support and scaffold their students in any discipline is through what they say in the classroom. How teachers talk and interact with their students is a major way in which teachers frame their pedagogies, model ways of thinking, and convey ideas about the subjects they are teaching (Lemke, 1990; Moje, 1995; Scott, 1998). In design education especially, talk interactions between teachers and students are a key component (Ferriera et al., 2015). Both the content and structure of teachers' talk influence the ways in which students understand, identify with, and find interest in engineering. Therefore, improvement in how teachers talk to their students about engineering design at all levels of students' educational experiences has the potential to better prepare students for success in engineering and increase the diversity of engineering fields (Cunningham & Lachapelle, 2014). However, in engineering education there are incomplete understandings on the most effective ways for instructors to interact with students during engineering design tasks. Additionally, since most precollege teachers have more expertise in education than engineering (Daugherty & Custer, 2014; Diefes-Dux, 2014; O'Brien et al., 2014) and most undergraduate engineering professors have more expertise in engineering than in education (Rotenberg, 2010), comparisons across these contexts have the potential to bridge gaps and synthesize work to capitalize on the strengths of instructors with different backgrounds.

My three-study dissertation examines the ways in which instructors use talk to interact with their students through a variety of different engineering design settings and contexts, with potential implications to improve and educate how teachers present engineering to their students. Overall, I address the research question:

> How do instructors (teachers and professors) use talk interactions to scaffold students in engineering design?

The following research questions are address in each of the three studies:

> Study 1: How does a middle school life science teacher use engineering talk during an engineering design-based STEM integration unit?

Study 2: How do teachers interact with small teams of middle school students as they work on engineering design projects during an engineering design-based STEM integration unit?

Study 3: How do professors use their talk as a tool to scaffold undergraduate students' learning during their work on engineering design projects in introductory engineering courses?

The studies in this dissertation look at several different ways in which instructors, both precollege teachers and college professors, use their talk to interact with their students during engineering design challenges. The first study is a case study that focuses on the whole class verbal interactions of an experienced and successful teacher throughout the entirety of a month-long life science-based STEM integration unit in a 6th grade classroom to address the research question: How does a middle school life science teacher use engineering talk during an engineering design-based STEM integration unit? The second study examines how 6^{th}, 7^{th}, and 8^{th} grade teachers use their talk to support teams while the students are actively working in small teams on engineering design projects, focusing on when the students are working in their teams on engineering design, to address the research question: How do teachers interact with small teams of middle school students as they work on engineering design projects during an engineering design-based STEM integration unit? The third study examines the talk interactions of professors of introductory, undergraduate engineering courses across engineering disciplines to address the research question: How do professors use their talk as a tool to scaffold undergraduate students' learning during their work on engineering design projects in introductory engineering courses?

1.1 Literature

Teacher talk in the classroom is an important avenue to bringing students into disciplinary talk and is a major way in which students are exposed to discipline-specific ways of communication (Moje, 1995). Teacher talk involves both the language and content of the talk (Lemke, 1990). Although engineering language has certain vocabulary and jargon that plays an important role in the field, which other studies have investigated (e.g. Wilson, 1999), students can learn the content of engineering talk before mastering the jargon and language (Berland et al., 2016; Christodoulou & Osborne, 2014; Jung & McFadden, 2018; Wendell et al., 2017). Therefore, the studies in this dissertation focus on the content of the instructors' talk during their interactions with students.

Teacher talk has been studied in a variety of settings. At the precollege level, teacher talk has been studied in many subject areas, including science and mathematics education (e.g. Dawes, 2004; Lemke, 1990; Tytler & Aranda, 2015). However, engineering at the K-12 level is much newer and less defined than other subjects (Brophy et al., 2008; National Academy of Engineering [NAE] & National Research Council [NRC], 2009) and therefore, has not been studied as extensively. At the undergraduate level, talk interactions between engineering students and professors has also been studied, especially talk during design reviews (e.g., Ferriera et al., 2015; Groen et al., 2015; Oak & Lloyd, 2015) but not in classrooms as thoroughly. Additionally, studies have analyzed engineering talk to define what it means to talk like an engineer (e.g., Dannels, 2002; Lande & Oplinger, 2014). Therefore, although together these areas of literature provide valuable insights into starting to understand the most effective ways for instructors to use their talk in classrooms, there is work to be done in the ways in which teacher talk can be used in the classroom to both capitalize on prior research in other subject areas, such as science and mathematics education, and other settings, such as design reviews, and to explore the discipline specific ways in which talk can be used in engineering classrooms.

Each unique discipline has unique practices, pedagogies, and ways of using talk, which play out in how teachers interact with their students. Engineering has its own unique ways of using talk in the classroom (Kittleson & Southerland, 2004). For example, Csomay (2007), in a study across university classes in six different disciplines, found that teachers in engineering used more context language than in natural sciences and that engineering classes contained less personalized references than other disciplines. Dannels (2002) found that engineering professors convey the idea that effective engineering presentations are simple, sell an idea, are numerically rich, are results-oriented, and are visually sophisticated. In mechanical engineering design reviews, Lande and Oplinger (2014) found that professors' questions were most often based on customer specifications, specific statistics about design parts, and the necessity of completing the project. Differences in talk across disciplines have been studied in teacher talk. For example, Bower (2005) analyzed the mathematics and physics talk of a teacher who taught courses in both subjects, and found that in algebra talk, the teacher was more likely to ask "questions focused on procedures," use "informal language to provide motivation for the meaning of certain terminology," and use "gestures to focus attention during talk" (p. 166). In physics talk, the teacher was more likely to ask "questions addressing scientific process and concepts," use "informal language combined with formal definitions," use "demonstrations and drawings to help 'tell' a story," and talk about the "inherent appeal and value of physics" (p. 166).

In design, talk is essential for conveying ideas to others, for developing ideas, and in the creation of ideas. Fleming (1998) stated that:

> language permeates the design process: it is used in the communication of constraints and requirements; in group problem-solving and decision-making; in designer-client dialogue and negotiation; in inquiry, research, and testing; in naming, specifying, presenting, and elaborating; and in evaluation, application, and interpretation. (p. 42)

Therefore, students must learn to talk design in order to truly learn engineering design (Atman et al., 2008). In design, language includes both the "language of designing," such as the language used between a pair of designers as they are developing an idea, and the "language about designing," the metacognitive use of language involving reflection and explanation of ideas (Schön, 1983). To help students learn both the language of designing and the language about designing, instructors often use their talk to model how designers think and how students should act in design (Dannels, 2002; Sonalkar et al., 2015), using a variety of pedagogical talk strategies. Groen et al. (2015) identified several of these strategies in expert/student interactions during design reviews, namely that experts make statements to students to acknowledge enthusiasm, advise, challenge, clarify, command, demonstrate expertise, evaluate, express satisfaction, extend, promote reflection, protect, and understand. Roth (1996) found that both whole class discussions and using artifacts to support talk were essential for students to develop engineering talk. Additionally, when "the language of engineering design...is oriented to the design process," rather than the solution itself, students more clearly see the importance of engineering design as a process, "rather than knowing engineering design as a set of solutions to a problem with few or no events in between" (Atman et al., 2008, p. 318). Furthermore, several studies suggest that for students to more authentically engage in design, instructors should act more as "coaches" or "tutors," rather than the end all expert in the classroom (e.g., Dannels, 2002; Oak & Lloyd, 2015).

The ways in which teachers utilize their talk set up how power is distributed in the classroom. Students' behavior is strongly affected by teacher talk (Pimentel & McNeill, 2013; Webb et al., 2009), and the ways in which teachers frame their interactions with students and use this power in the classroom play a major role in the classroom environment and in how students think and approach problems. Teachers often use their talk to maintain their control of the classroom and the students' ideas, often working to guide their students to the "right" answer (Berland & Hammer, 2012; Bleicher et al., 2003; Scott, 1998). However, when teachers talk authoritatively in a closed manner that is focused on the "right answer," students responses are often shorter and less meaningful and students are more likely to ask questions to the teacher directly rather than consulting peers (Cummings et al., 2015; Pimentel & McNeill, 2013; Scott, 1998). It is essential that teachers develop a classroom environment that is well-managed and organized. However, to authentically practice engineering design projects, which do not have a "right" answer, students must have control of their design ideas and students need to feel empowered to make their own decisions based on their experience and knowledge (Jung & McFadden, 2018). In order to achieve this empowerment, teachers must let go of some of their own control, giving students the freedom to develop their own ideas. The ways in which teachers talk to their students strongly affects this dynamic. For example, when teachers use their communications with students to convey positive social messages, motivating their students with positive relationships, rewards, and modeling, students learn more than when teachers use their power directly or coerce students (Plax et al., 1986). Open-ended questions, reflective questions, and prompts for conceptual understanding support students in argumentation and providing evidence for their ideas and elicit student thinking (McNeill & Pimentel, 2010; Ong et al., 2016; van Zee et al., 2001). Additionally, learning is fostered when teachers refrain from giving answers directly and use "reflective discourse" to convey the message that they as the teacher are also working to develop their understandings along with students (Scott, 1998; van Zee & Minstrell, 1997). This requires power dynamics in the classroom that yield some of the control to the students. This cannot happen if they are being told directly what to do by the teacher. Therefore, the teacher must walk the line between giving too much guidance as to overly constrain the students' ideas and giving too little guidance that would lack the support students need to practice complex design processes and communicate with their peers.

Another way that teachers use their talk is to elicit student ideas to formatively assess their students (Leung & Mohan, 2004; Ruiz-Primo & Furtak, 2006). Teachers need to "find out what children think and to organize ways of helping them to question their own ideas and those of others" (Dawes, 2004, p. 678). Teachers need to formatively assess their students to gain a complete picture of students are learning, including where students are so that they can provide effective scaffolding (Wood et al., 1976). Instructors often use their questions to formatively assess students and better understand what students know or how they approach problems. For example, Cummings et al. (2015) found that in mechanical engineering design reviews, professors often asked questions that required students to defend their ideas or to explain how they had anticipated different parts of the problem. Additionally, instructors also use their talk to model the types of things that students should think about to assess their own work (Oak & Lloyd, 2015).

1.2 Theoretical Framework

Design is a core practice of engineers to the point where "design is often defined as synonymous with what engineers 'do'" (Daly et al., 2012, p. 187). For example, some authors use the terms engineering design and engineering interchangeably (Johnson, 2009; Petroski, 1996) because the two concepts are so interconnected. Additionally, a common measure of students' engineering literacy is their ability to apply the engineering design process to a new situation (Becker & Mentzer, 2015; Sneider & Purzer, 2014), and the ability to design is seen as a core outcome at all levels of engineering education (ABET, 2018; Froyd et al., 2012; NAE & NRC, 2009; NGSS Lead States, 2013).

However, design is challenging. Design problems are complex, ill-structured, and have multiple solution paths (Daly et al., 2012; Gainsburg et al., 2016; Jonassen et al., 2006; Simon, 1969). They require use of technical and social skills, iterative processes, and limited resources (Johnson, 2009; Jonassen et al., 2006). Designers must be able to balance trade-offs and competing criteria, use evidence to make decisions, consider multiple stakeholders, and apply knowledge from a vast range of disciplines (Atman et al., 2007; Daly et al., 2012; Dym et al., 2005; Jonassen et al., 2006; McKenna, 2007). For students and inexperienced designers, many of these factors are challenging. For example, beginning designers often treat design tasks as well-defined, skip doing research about the problem, quickly jump into solution generation, become fixated on an idea, make decisions without weighing evidence, and conduct few, non-analytical tests (Crismond & Adams, 2012).

However, in order to learn how to design, engineers and engineering students must practice design, including complex and ill-structured design projects that exist outside of their abilities to work by themselves. To help them succeed, a more knowledgeable other can provide scaffolding for their learning (Vygotsky, 1986; Wood et al., 1976 also e.g., Cohrssen et al., 2014; Kawalkar & Vijapurkar, 2013; van de Pol et al., 2014). In the classroom, the instructors, whether precollege teacher or college professor, in addition to more knowledgeable peers, act as this more knowledgeable other. Teachers provide scaffolding to their students through a variety of decisions in the classroom, including the instructional materials that they use, the structure of their classroom, and the complexity of problems that they choose to give to students. However, the ways in which teachers use their talk to interact with students is an essential aspect of scaffolding. The teachers actions of "explain[ing], suppl[ying] information, question[ing], correct[ing], and ma[king] the pupil explain" (Vygotsky, 1986, p. 191) allow the students to bridge their zone of proximal development to be able to understand concepts and solve problems that they could not do alone. The ways in which teachers talk to their students are essential for scaffolding many aspects of learning, such as how they think about problems, how and if they seek help, and how they use their own language (e.g., Fleming, 1998; Lemke, 1990; Nathan & Kim, 2009; Scott, 1998). The teachers' language also contributes to how the students will continue to think about engineering concepts after the teacher has stopped their support (Jones et al., 2014; Williams et al., 2011). The different ways in which teachers use their language in the classroom, such as whether they are talking to the whole class, teams, or individual students and the relative difficulty of the problem solving or design tasks, utilize scaffolding strategies in different ways. Therefore, to gain a more complete picture of how engineering teachers and professors use talk as a scaffolding tool, teacher talk must be analyzed in different settings.

1.3 Methods

There are many different aspects to teacher talk that work in conjunction with each other to frame the pedagogies that instructors use. In order to examine these, this three-study dissertation uses case study (Creswell & Poth, 2018; Yin, 2018) and naturalistic inquiry (Lincoln & Guba, 1985) methods to examine three different settings of classroom talk. These approaches allow observations and examinations of the actions of teachers in their classrooms without disturbing their natural practices to address the research question: How do instructors (teachers and professors) use talk interactions to scaffold students in engineering design? Further explanations of each studies' specific methodology are described in more depth in each studies' methods sections.

Although each study was conducted in different settings, they have similar foci, namely, instructor talk interactions during engineering design in classrooms. The studies' designs and motivations inform each other. The first study was conducted with the motivation to better understand the whole class verbal interactions of a teacher who had previously demonstrated exemplary teaching pedagogies in an effort to better understand his success. In the process of conducting this study, I wanted to further explore the interactions of teachers with small teams of students as teachers interact in much different ways than in whole class settings because the ways in which teachers interact with their students is not limited to just how they talk to all students. This idea lead to the development of the second study. Additionally, I became interested in how different aspects of engineering talk work together in different settings. This prompted me to look into different settings of classroom talk and to develop the third study. Although the studies inform each other, each study was conducted independently with different sources of data and different analysis methods, which are described in depth in each chapter. The final chapter of this dissertation includes a synthesis and comparison across the three studies.

2. ENGINEERING AS THE INTEGRATOR: A CASE STUDY OF ONE MIDDLE SCHOOL SCIENCE TEACHER'S TALK

A version of this chapter has been published in the Journal of Engineering Education:

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2.1 Abstract

Background Integration of engineering into middle school science and mathematics classrooms is a key aspect of STEM integration. However, successful pedagogies for teachers to use engineering talk in their classrooms are not fully understood.

Purpose This study aims to address this need with the research question: *How does a middle school life science teacher use engineering talk during an engineering design-based STEM integration unit?*

Design This case study examined the talk of a teacher whose students demonstrated high levels of learning in science and engineering throughout a three-year professional development program. Transcripts of whole-class verbal interactions for 18 class periods in the life science-based STEM integration unit were analyzed using a theoretical framework based on The Framework for Quality K-12 Engineering Education.

Results The teacher used talk to integrate engineering in a variety of ways, skillfully weaving engineering throughout the unit. He framed lessons around problem scoping, incorporated engineering ideas into scientific verbal interactions, and aligned individual lessons and the overall unit with the engineering design process. He stayed true to the context of the engineering challenge and treated the students as young engineers.

Conclusions This teacher's talk helped to integrate engineering with the science and mathematics content of the unit and modeled the practices of informed designers to help students learn engineering in the context of their science classroom. These findings have the potential to improve how educators and curricula developers utilize engineering teacher talk to support STEM integration.

2.2 Introduction

Engineering plays a vital role in the meaningful integration of science, technology, engineering, and mathematics (STEM). Incorporating engineering in pre-college curricula provides many advantages, including supporting success in mathematics and science learning, raising awareness of opportunities in engineering, promoting understanding and implementation of engineering design, and enhancing technology literacy (NAE & NRC, 2009). Recent education reform efforts throughout the world aim to reach these goals and call teachers to integrate engineering practices and content into their science, mathematics, and technology classes. For example, Australian Council of Learned Academies (2013) calls for increased expectations for students to enroll and excel in STEM courses. In Scotland, the same need for improvement in STEM courses is met with a call for students to have more engagement with "real life science, engineering and technology," for teachers to build their expertise, and for schools to provide more support for teachers and learners by improving "in the area of curriculum, qualifications, assessment, and careers advice" (Education Audiovisual and Culture Executive Agency (EACEA P9 Eurydice), 2011, p. 30). In the United States, the Next Generation Science Standards (NGSS) call teachers at all levels to integrate engineering into their science classes by teaching both science and engineering practices, making "instructional decisions" to teach students to define problems, conduct thorough processes to make decisions, optimize solutions, and make connections across subject areas (NAE & NRC, 2009; NGSS Lead States, 2013).

In the Case for STEM Education, Bybee (2013) identified three challenges to implementing STEM education: (1) actively integrating technology and engineering, (2) introducing STEM-related contexts as a means to educate students in STEM disciplines, and (3) defining STEM for educational purposes. His work focuses on systemic challenges including purpose, policy, programs, and practice. However, considering just the classroom practice aspects of the challenges, we see that integrating engineering and technology, using contexts to meaningfully teach STEM, and defining STEM are significant challenges in themselves. Sometimes the definition of STEM puts each discipline in silos, but when integration of the disciplines is the focus, there are additional burdens to effective teaching, especially since most pre-college teachers have limited experience and understanding of engineering because their teacher training programs have not included engineering (Hynes, 2010; NAE & NRC, 2009). Therefore, teachers without engineering experience tend to be less comfortable discussing engineering with their students than with disciplines they have more background with (Brophy et al., 2008; Capobianco et al., 2011; Hynes, 2010), posing challenges for teachers to optimize their talk (Newton & Newton, 2001).

To address this issue, our recent work has studied a variety of teaching pedagogies and classroom talk in engineering and science units (Aranda et al., 2018; Guzey, Ring-Whalen, et al., 2017; Guzey & Ring-Whalen, 2018). In these studies, one teacher's classroom practices heavily reflected the pedagogies espoused in our professional development program as well as demonstrating ways to overcome the challenges to practice laid out by Bybee (2013). Mr. Evans, a middle school science teacher, used classroom talk and integrated engineering into his science classroom effectively, demonstrated by his students' high learning gains (Guzey & Ring-Whalen, 2018). Therefore, the purpose of this study is to build upon this prior work and analyze in more depth the teacher talk pedagogies that Mr. Evans used. A better understanding of his practices can provide details to help teachers and educators more effectively use engineering talk to support STEM integration. In this study, we address the research question: How does a middle school life science teacher use engineering talk during an engineering design-based STEM integration unit?

2.3 Background

2.3.1 Teacher Talk

Teacher talk is an important avenue to bring students into disciplinary talk and is a major way in which students are exposed to discipline specific ways of communication (Moje, 1995). This is especially important in engineering where the discipline has complex and vastly different subdomains of content, actions, and communication that must simultaneously be employed (Crawley et al., 2014). When used excessively teacher talk detracts from student-centered teaching (McNeill et al., 2013). However, when used appropriately, teacher talk plays an important role in guiding and scaffolding students' classroom activities and learning (Dawes, 2004; McNeill & Krajcik, 2007; Scott, 1998; Viiri & Saari, 2006). As Roth (1996) has observed in fourth and fifth grade students learning engineering, "whole-class interactions play a central role" in tying together the "various experiences they shared" (p. 114) and the many components of engineering. However, there is limited research on whole-class verbal interactions in pre-college engineering.

Teacher talk involves both language and content of talk (Lemke, 1990). Engineering language has vocabulary and jargon that play important roles in the field, which other studies investigated in classrooms (e.g., Wilson, 1999). However, middle school students do not need to be comfortable with high levels of jargon to convey their engineering ideas (Wendell et al., 2017). Teachers can portray many of the ideas of engineering and model engineering talk through the content of their talk with everyday language. Students can frame arguments and give evidence for their ideas with everyday language (e.g., Berland et al., 2016; Christodoulou & Osborne, 2014) that allows them to authentically practice engineering (Jung & McFadden, 2018). In fact, young students' scientific understandings are often underestimated and misunderstood if assessment is based primarily on their language use (Bleicher et al., 2003; Blown & Bryce, 2016). The language of engineering can be improved as students develop more complex disciplinary knowledge. Therefore, in this study, we focus on the content of the teacher's engineering talk rather than the particular language used. We use the theoretical framework described later in this paper to define engineering talk.

2.3.2 Teaching engineering

Teacher talk is a major way in which teachers frame their pedagogies. Pedagogies for teaching engineering have unique challenges that differentiate it from teaching other scientific disciplines. Although many factors play into this difficulty (Wendell et al., 2014), many of these challenges align with difficulties students face with the complexity of engineering design (Crismond & Adams, 2012). Engineering design is a complex endeavor that requires the designer to consider different interacting issues, such as the problem, the client and stakeholders, the needs to be met, the solutions that have been implemented to solve similar problems, the limitations put upon the designer by the client or the physical world, the need to prototype, the iterative nature of design, et cetera (Dym et al., 2005). Informed designers are able to use design strategies in a systematic way to follow the design process in an iterative manner, develop and balance multiple competing solutions to a complex problem, consider tradeoffs of each solution, problem scope by conducting relevant research, and conduct valid tests on their solutions whereas novice designers struggle with these skills (Crismond & Adams, 2012; Daly et al., 2012).

Due to the complexity of engineering design, it is not surprising that research has found that middle school students, novice designers, approach engineering problems very differently than expert engineering designers and that engineering design and problem scoping are teachable skills (e.g., Atman et al., 2007; Cantrell et al., 2006; Crismond & Adams, 2012; Enderson & Grant, 2013; English et al., 2013; Ganesh & Schnittka, 2014; Mentzer et al., 2015). Students need to be taught several key engineering skills that are important elements of design (Atman et al., 2007; Crismond & Adams, 2012; Dym et al., 2005). For example, students often jump into solution generation more quickly than experts and need to learn to problem scope (Atman et al., 2007), asking relevant questions and identifying criteria and constraints. Young students often do not have the skills to effectively identify the information they need and gather that information. Although many children are creative thinkers, teacher guidance can help them use their creatively more effectively and expand their thinking.

Engineering pedagogy has much in common with other STEM disciplines, such as the benefits of problem and project-based learning and inquiry learning, that science, technology, and mathematics teachers are familiar with and may be able to capitalize on in their engineering teaching. However, engineering also requires some pedagogical strategies that are unique to engineering design-based teaching (Capobianco & Rupp, 2014; Carr & Strobel, 2011; Fortus et al., 2004). For example, Crismond and Adams (2012) suggest several pedagogical strategies to help students move towards becoming more informed designers. They suggest that teachers and curricula have students "state criteria and constraints from design brief in one's own words," "write product history report," and "do rapid prototyping using simple materials or various drawing tools" (p. 748). Other research suggests that integrating the engineering context across the entire unit, rather than just a culminating project after the content has been taught, provides motivation to learn engineering and science (Guzey, Moore, & Morse, 2016; Guzey, Moore, Harwell, et al., 2016). However, these varied pedagogies provide challenges for teachers without engineering experience. For example, Capobianco and Rupp (2014) found that middle school teachers during engineering design-based instruction tend to struggle with "completing the different phases of the engineering design process and applying scientific principles during the task" (p. 263). Hynes (2010) found that middle school teachers are most comfortable explaining later stages of the engineering design process, especially constructing prototypes and redesign, and are less comfortable with earlier stages of the design process. The teachers in that study were able to lead in-depth discussions with their students about prototypes and redesign, possibly because they were more comfortable with these more concrete aspects of design.

Finally, teaching engineering also includes helping students see themselves as engineers. Studies have shown that helping students identify as engineers increased their views of who can be engineers (Capobianco et al., 2011; Pantoya et al., 2015). Furthermore, in a first-year engineering program, Lindsay et al. (2008) purposefully designated and treated their students as "student engineers" rather than "engineering students" to help them gain the skills of practicing engineers. They found that students perceived their work as the work of engineers rather than just coursework and that students began to integrate the practices of engineers with the technical aspects of engineering. These studies suggest that instruction designed to help students build conceptions of the work of engineers may lead to better outcomes in classrooms. However, the ways to effectively do this, especially with young children, are unclear. Together, these studies on teaching engineering suggest that more research needs to be conducted to develop knowledge about teacher pedagogies to better support teachers' instruction in engineering and engineering design and capitalize on teachers' strengths that may carry over from the disciplines they have more experience with.

2.4 Theoretical Framework

To guide our identification of engineering talk and analysis of the ways engineering talk is used, we adopted a theoretical framework that encompassed a holistic view of engineering. To classify engineering talk, this study was framed by The Framework for Quality K-12 Engineering Education (Moore, Glancy, et al., 2014), a comprehensive framework for classifying engineering learning at the pre-college level. The framework consists of nine indicators of quality engineering education, namely: 1. Complete process of design, 1a. Problem and background, 1b. Plan and implement, 1c. Test and evaluate, 2. Apply science, engineering, and mathematics, 3. Engineering thinking, 4. Conceptions of engineers and engineering, 5. Engineering tools, 6. Issues, solutions, and impacts, 7. Ethics, 8. Teamwork, and 9. Communication related to engineering. Each indicator is an essential component of engineering education, especially at the pre-college level, and is described in the following sections. This framework was developed over the course of five iterations using consultation with experts, Accreditation Board for Engineering and Technology [ABET] criteria, K-12 state standards, national policy reports, and applications in classrooms. "The framework is designed to be used as a tool for evaluating the degree to which academic standards, curricula, and teaching practices address the important components of a quality K-12 engineering education" (p. 1). It has been used to characterize standards, look at teacher practice, characterize students' ideas about engineering, frame engineering within STEM integration, and develop curricula (e.g., Dare, 2015; Herro & Quigley, 2017; Kersten, 2013; Moore et al., 2015;

Ortmann, 2015; Wilson-Lopez et al., 2016). Here, we use it to classify whether or not teacher talk falls within the bounds of engineering talk.

2.4.1 Process of design (POD)

Engineering design is a core practice of engineering (Dym et al., 2005; Mentzer et al., 2015; NRC, 2012) because engineers scope, generate, evaluate, and realize ideas (Sheppard, 2008) to problems that have more than one correct answer. The engineering design process, including problem scoping, planning, testing, redesigning, and communicating, is a systematic and iterative process that engineers use to develop technologies and solutions to complex problems and is a key component of engineering education for students to learn to solve the complex and ill-structured problems of engineering (Jonassen et al., 2006; NAE & NRC, 2009). Although many different representations of the design process are in use and available, The Framework for Quality K-12 Engineering Education (Moore, Glancy, et al., 2014) was developed to include fundamental characteristics of the engineering design process based on the different representations.

The Framework divides the design process into three interconnected stages, Problem and Background (POD-PB), Plan and Implement (POD-PI), and Test and evaluate (POD-TE). During POD-PB, students work to understand what the client needs; the criteria, constraints, and requirements needed to frame the goals of the problem; and collect information to learn about and define the problem (Atman et al., 2007; Dym & Little, 2003; Jain & Sobek, 2006; Moore, Glancy, et al., 2014; Yang, 2005). During POD-PI, students brainstorm multiple ideas, balance these multiple ideas as they develop, and consider tradeoffs of each design to choose a solution (Moore, Glancy, et al., 2014). Implementation of their idea often takes the form of a prototype or detailed design plan, depending on the format of the design problem. During POD-TE, students learn to develop appropriate tests, evaluate their solutions, select a potential solution from among many, and troubleshoot solutions to meet criteria and constraints.

2.4.2 Apply science, engineering, and mathematics (SEM)

Engineers work within the physical constraints of nature and "engineers must also be knowledgeable about science—typically physics, biology, or chemistry—that is relevant to the problem they are engaged in solving" (NRC, 2010, p. 7). Therefore, to authentically engage in engineering design, students need to have opportunities to use appropriate mathematics and science concepts and skills to solve engineering problems (NAE & NRC, 2009).

2.4.3 Engineering thinking (EThink)

In addition to the technical skills, engineers need ways of thinking that are independent, reflective, metacognitive, creative, persistent, and innovative (Moore, Glancy, et al., 2014; NAE, 2004). These ways of thinking include design thinking and systems thinking (Cross & Cross, 1998; Dym et al., 2005; NAE & NRC, 2009), which are difficult to learn and take practice over periods of time and contexts to develop (Atman et al., 2007; Dym et al., 2005; Moore et al., 2015). Engineering thinking is an essential skill for engineers to be successful and "engineering design thinking can support students' STEM learning, enhance knowledge and abilities, and build interest in STEM fields" (Mentzer et al., 2015, p. 428).

2.4.4 Conceptions of engineers and engineering (CEE)

To be successful engineers in their future and to be informed citizens, students need to have accurate ideas of engineering and engineers (Moore, Glancy, et al., 2014). Many students have limited exposure to engineering, which can lead to misconceptions about the profession (Ganesh & Schnittka, 2014). For example, many students associate engineering simply with fixing and building things and with engineers being male (Capobianco et al., 2011). These misconceptions result in many students dropping out of engineering, mathematics, and science courses before they have opportunities to demonstrate their skills or gain a complete understanding of their potential success as engineers.

2.4.5 Engineering tools, techniques, and processes (ETools)

Engineering tools, techniques, and processes are necessary for engineers to produce a product. Engineering tools are objects used to make work easier and efficient (e.g., hammers, calipers, calculators, software). Techniques are step-by-step instructions for specific tasks to solve them (e.g., DNA isolation). Processes are collections of steps or actions to reach an end product (e.g., production, manufacturing) (Moore, Glancy, et al., 2014). Students must be familiar with the tools of engineering and given time to use and learn the tools' function before applying them to engineering problems (Crismond & Adams, 2012). ETools includes many of the technology aspects of STEM integration called for in the NGSS (NGSS Lead States, 2013).

2.4.6 Issues, solutions, and impacts (ISI)

Students need to understand the impact of their solutions in global, economic, environmental, and social contexts to solve the complex problems they will encounter in the world. Students need to have knowledge of current events and issues, locally and globally, such as transportation and water supply issues, to be able to develop solutions for realistic problems and to investigate the effects of their solutions (Moore, Glancy, et al., 2014).

2.4.7 Ethics

Ethics require engineers to "perform under a standard of professional behavior that requires adherence to the highest principles of ethical conduct" to "hold paramount the safety, health, and welfare of the public" (National Society of Professional Engineers, 2007). Ethical considerations, including safety and environmental considerations, governmental and professional standards, integrity in work, and respect for intellectual property (ABET, 2018; Moore, Glancy, et al., 2014; NAE & NRC, 2009), are important aspects of engineering that needs to be instilled at all levels of engineering education (Barakat, 2011; NRC, 2012). Practicing engineers must conduct themselves in accordance with the ethics of their profession and budding engineers at the pre-college level need to practice these ethics.

2.4.8 Teamwork (Team)

Engineers often work in teams because of the nature of the complex problems they solve (Jonassen et al., 2006). Learning to be an effective and contributing member of a team is an important aspect of engineering education (NAE & NRC, 2009). Additionally, "collaboration and teamwork afford students rich opportunities to develop expertise and identity as valued science and engineering contributors" (Cunningham & Lachapelle, 2014, p. 126). To learn to work productively in teams, students need to learn teamwork skills such as the ability to listen to and accept diverse viewpoints and include all members of their team (Dym et al., 2005; Moore, Glancy, et al., 2014).

2.4.9 Communication related to engineering (Comm-Engr)

Communication is an essential component of engineering throughout the engineering design process and in the communication of a final product (ABET, 2018; Acosta et al., 2010; NAE & NRC, 2009). Engineers communicate in a variety of formats, including verbally and written, using symbols, drawings, and equations, and to a variety of audiences. Engineering requires both general communications skills (e.g., the ability to explain one's ideas) and engineering specific communication skills (e.g., the ability to communicate technical information to other engineers and stakeholders) (Moore, Glancy, et al., 2014).

Implementing engineering in an authentic manner in the classroom is challenging for many teachers. The pedagogies introduced in the literature review are multifaceted and require an understanding of the holistic nature of engineering and engineering design. This study focuses on how one teacher used engineering talk to facilitate engineering design-based STEM integration instruction.

2.5 Research Design and Methods

2.5.1 Approach

This study addressed the research question: How does a middle school life science teacher use engineering talk during an engineering design-based STEM integration unit? We used a case study approach to examine the engineering teacher talk of an experienced middle school life-science teacher during an engineering design-based STEM integration unit. A case study approach allowed us to investigate teaching processes in a specific, bounded context (Yin, 2018) and is a commonly used method to study classroom talk (Christodoulou & Osborne, 2014; Moje, 1995; Tytler & Aranda, 2015) because it allows an in-depth analysis of one teacher's practices to achieve a deep understanding of the nuances and details of teacher talk within a specific classroom. Additionally, in conjunction with our theoretical framework, the case study approach allowed us to closely examine each of the indicators of quality K-12 engineering education within the teacher's talk. Although findings from our single case study approach are not generalizable to all classrooms, they can provide important insight into how engineering talk is used. This study was conducted as part of the EngrTEAMS project, an NSF-funded project focused on curriculum development, teacher professional development, and research on upper elementary and middle school STEM integration.

2.5.2 Case Description

The study was conducted in Mr. Evans's (pseudonym) sixth grade life-science class located in the midwestern United States over the course a month-long engineering design-based STEM integration unit. The curriculum is described in depth later in this section. The unit was implemented in the spring; therefore, the students had been members of Mr. Evans's classroom for several months and were accustomed to his classroom procedures and style. Table 2-1 displays the demographics of the school. Mr. Evan's was teaching a 6^{th} grade science class where students had not been tracked into levels.

Table 2-1. *School Demographics*

Variable	Percentage of Student Population
Race/ethnicity	
White, non-hispanic	73
Black, non-hispanic	9
Hispanic	6
Asian	12
Special Ed.	10
ELL	3
Free/reduced lunch	9

At the time of this study, Mr. Evans had eight years of science teaching experience. He demonstrated high interest and motivation for integrating engineering into his teaching, as shown by his choice to participate in a STEM integration professional development summer program for three years prior to the implementation examined in this study. Over the course of these three years, Mr. Evans stood out as an effective teacher (Guzey & Ring-Whalen, 2018), who incorporated many engineering and pedagogical practices that strongly supported student learning. In the same study, Mr. Evans described that he believes that treating his students as engineers motivates them and increases their engagement. When compared to students of other middle school teachers using the same curriculum in their middle school life-science classes, Mr. Evans's students performed significantly higher on science posttests after completion of the unit (Guzey, Ring-Whalen, et al., 2017). We also studied Mr. Evans's use of teacher talk strategies such as asking thought-provoking questions and elaborating on students' responses during implementations of three STEM units over three years (Guzey & Ring-Whalen, 2018). Our analyses demonstrated that the detail and depth in his science and engineering talk while asking thought-provoking questions and elaborating on students' responses increased over the years, and he was able to successfully navigate through various classroom practices and classroom conversations involving science and engineering. However, these studies analyzed pieces of Mr. Evans' talk, such as questioning strategies, and compared his strategies to other teachers. The purpose of this study was to further and more holistically examine how he used engineering talk to achieve this success, looking at all of his talk to the whole class, rather than specific pieces.

The professional development program in which Mr. Evans participated was implemented by the authors and other science and engineering education researchers to help the teachers improve their understanding of engineering and practices of engineering design-based science teaching. Over the course of three weeks in each summer, the teachers spent time learning about science and engineering and developing curricular materials to integrate engineering design with the science content that they were already teaching. They designed their curriculum units to align with state standards and the NGSS (NGSS Lead States, 2013) and to present a meaningful and engaging context, drawing on their experiences as teachers and their knowledge of topics of interest to their students. Additionally, they worked to frame the unit around student-centered pedagogies and incorporate what they learned during the professional development program about engineering design-based instruction, which included a very brief introduction to the Framework for Quality K-12 Engineering Education but was not a focus of any of the professional development program. To evaluate the quality of the unit, the teachers tested their first iteration with a group of summer camp students and made changes based on their experiences. The research presented here is focused on the second iteration of the unit, which included these changes, as Mr. Evans implemented it in his classroom.

At the start of the unit, students were approached by a client, in the form of a letter, and asked to solve the client's problem: farmers with genetically modified organism (GMO) crops need to keep their fields separated from non-GMO farmers. To develop their solution, teams worked together to learn, plan, build, test, and redesign their solution and present it to the client in the form of a letter. To test their solutions, students constructed prototypes from a selection of materials and tested them using a fan and glitter to represent the wind and pollen, respectively. Lessons included student-centered activities, including a debate over the regulation of GMOs, DNA model construction and analysis, and analysis of traits within students' own families. The students learned about and utilized a model of the engineering design process that was included in the curriculum. The design process included the stages of define, learn, plan, try, test, decide. For the purpose of this research, we considered only the data from the unit in which the teacher was addressing the whole class. Table 2-2 provides a brief overview of the topics for each class period that were discussed in whole class settings. The unit covered the NGSS main ideas for middle school engineering design standards (NGSS standard MS-ETS1) and middle school life science (NGSS standard MS-LS3) standards for Heredity, Inheritance and Variation of Traits as well as the crosscutting concepts: cause and effect and structure and function. The unit also included eight science and engineering practices recommended in the NGSS: defining problems, developing and using models, planning and carrying out investigations, analyzing and interpreting data, using mathematics and computational thinking, designing solutions, engaging in argument from evidence, and obtaining, evaluating, and communicating information.

Table 2-2. Outline of the STEM integration unit used in Mr. Evans's Classroom.

Lesson	Day(s)	Focus of Whole Class Verbal Interactions	Class time included in transcripts (out of 50 minutes)
1. Introduction of Engineering Challenge	1	What is engineering?; Introduction to the engineering challenge with the client letter	35 min.
	2, 3	Basics of GMOs; Debate for or against regulation of GMO crops	25 min., 35 min.
2. Introduction to DNA Structure and Function	4, 5, 6, 7	Structure of DNA and chromosomes using a balloon model and an origami model; DNA extraction lab	30 min., 25 min., 30 min., 40 min.
3. Genes and Trait Expressions	8	Traits of family members; Dominant and recessive genes and traits	45 min.
4. Introduction of Heredity	9, 10	Sexual and asexual reproduction; Mitosis and meiosis; Relationships between these ideas	35 min., 35 min.
5. Applied Heredity	11	How to use Punnett squares to study heredity	35 min.
6. Genetic Modification	12	Genetic modification using plasmids; Students construct a paper model of a plasmid	30 min.
7. Scale Model Research	13, 14	Reasons to use scale models; How to perform scale model calculations	15 min., 30 min.
8. Engineering Challenge	15, 16	How to plan and build solution to the engineering challenge	15 min., 15 min.
	17, 18	Solution testing procedures; Prepare to present solution idea to the client	15 min., 15 min.

2.5.3 Data Collection Procedures

We examined eighteen 50-minute long class periods (around 15 hours of instruction) in Mr. Evans's classroom. All lessons were video recorded and transcribed. This study focused on whole-class verbal interactions when Mr. Evans's talk was accessible to all students. Transcripts included both what Mr. Evans said to his students as well as the students' responses and questions during whole-class interactions. However, because at this point in the data collection the cameras and audio were trained on the teacher, student talk was sometimes difficult to decipher. This did not affect the quality of this research or the analysis since the purpose of the study was to understand engineering disciplinary content patterns within the teacher talk. The transcripts included in this study consisted of a total of 152 pages and 62,500 words. In addition to the recording of each class period, we also kept field notes and documented student work through images of their engineering notebooks and final products. Although we did not directly analyze these data sources, they were an important reference to understand classroom format and how Mr. Evans organized his classroom.

2.5.4 Data Analysis Procedures

We based our analysis procedures on the analytic strategy *pattern matching* laid out by Saldaña (2016 and Yin (2018). Pattern matching compares an empirically-based pattern with a predicted pattern, i.e., using an a priori coding scheme. Pattern matching is appropriate for this descriptive case study as we chose to use a tested framework for our coding scheme and matched the patterns in our data to this framework. First, we used the computer-assisted tool NVivo 11 to look for patterns in the data by coding all the transcripts of whole-class verbal interaction using the coding scheme that included each of the nine indicators in the theoretical framework. Two of the authors first individually coded the transcripts, considering only talk that fit within the framework of engineering talk and excluding talk unrelated to engineering from the analysis. We coded the data at a sentence level. Throughout the coding process, we regularly met to resolve disagreements and code to consensus, consulting the other authors as needed for verification or to resolve disagreements. During this process, we developed subcodes as needed within several of the indicators (see Figure 2-1). Selected examples of each code are provided in Figure 2-2.

1. Complete Process of Design (POD)

1a. Problem and background (POD-PB)	1b. Plan and Implement (POD-PI)	1c. Test and Evaluate (POD-TE)
Subcodes:		
Client	*Brainstorm*	*Iterate*
Constraints	*Plan*	*Test*
Criteria	*Implement*	*Evaluate*

2. Apply Science, Engineering, and Mathematics

Subcodes:

Mathematics

Science

3. Engineering thinking (Ethink)

4. Conceptions of engineers and engineering (CEE)

5. Engineering tools, techniques, and process (ETools)

6. Issues, solutions, and impacts (ISI)

7. Ethics

8. Teamwork (Team)

9. Communication related to engineering (Comm-Engr)

Figure 2-1. Codes and subcodes, based on the theoretical framework

Code	Example from Mr. Evans's Talk
Process of Design (POD)	POD-PB: DNA's the focus because we know that GMOs are determined by DNA, and so once we understand the reproductive strategies, that can help us understand our client's concern with the word cross-pollination which as we know is a sexual reproduction strategy (Day 10). POD-PI: Yeah, make a blueprint or you have to do a brainstorm. You have to have a plan. If I just cut you loose and said go use up the supplies, in real life you'd probably cost our classroom a lot of money because you would just start gluing all this stuff and then be like, no, I don't want to do that and grab new stuff (Day 15). POD-TE: You're going to create something that will prevent pollen. We're going to use glitter. The glitter's going to start out here. We're going to put some amount, some mass, of glitter and use the fans. Low power and high power to represent low and high gusts of wind. We're going to use the fan to blow the glitter and what you'll do is measure the mass of glitter that we end up with actually getting to the organic farm (Day 15).
Apply Science, Engineering, and Mathematics (SEM)	Mathematics: That's the actual size. The perimeter of the organic farm you [have]. Someone describe [it] to me. I don't need the number right now, I want you to tell me how did you figure out the perimeter of the organic farm? (Day 14). Science: Here's the child, and remember in sexual reproduction the child's gonna get half the DNA from mom and half the DNA from dad, so see if this makes sense. See if you think this person could be the father, yes or no, talk to your group (Day 10).
Conceptions of Engineers and Engineering (CEE)	As an engineer, you're going to have to use math, you're going to have to use science, okay? You're going to have to use a lot of different skills (Day 5).
Engineering Tools (ETool)	You're going to create a GMO with paper. You're going to get a plasmid. You're going to get a plasmid, each of you is going to get a plasmid. You're going to cut it out. Cut it out so that it looks like that (Day 12).
Issues, Solutions, and Impacts (ISI)	Think about how it might impact the crops (Day 15).
Ethics	So the question is, since GMOs are relatively new- we're talking the last 10 to 20 years- we might in 20 years know more about pesticides and things like that and how they impact us. So that's one of the concerns that people have about GMOs. Not so much that they are GMOs, but rather as a result, oftentimes they get doused with more chemicals and things like that (Day 3).
Teamwork (Team)	I want you to chat with your table groups about what you see up there on the screen. Chat with your groups. Tell each other what you think you're seeing and why (Day 6).
Communication to Engineering (Comm-Engr)	Draw your final design with labels. Sketch it, label it, the cost of everything and this and that. Put all that information in your notebook before you leave today (Day 18).

Figure 2-2. Example talk representing each code and sub-code

The coded transcripts provided raw data for when Mr. Evans talked about each indicator. To make sense of this data, the next stage of our analysis used the coded transcripts to look for themes. We generated process flowcharts, as a form of chronological sequences (Yin, 2018), from the coded transcripts. We developed the flowcharts by breaking down the order and time spent on each of the codes. The flowcharts provided a visual representation of Mr. Evans's engineering talk by illustrating its order, time spent, and sequential logic. Because the instances of each code varied greatly in length from a few words to several minutes that were unrealistic to time stamp, we characterized instances by the number of lines of transcript they encompassed. To look for themes across the data, we spend a significant amount of time analyzing the flowcharts individually and as a group, looking for patterns across individual days and across multiple days. These patterns ranged from short back and forths between students to longer, multiple day procedures. We compared the flowcharts and patterns to the transcripts to further break down what Mr. Evans was saying. As we engaged with the data, we used these patterns to develop themes around the codes. Descriptions of these themes are described in the results and discussions sections.

2.5.5 Trustworthiness

We employed strategies to ensure trustworthiness in our analysis (Lincoln & Guba, 1985), based in part on the list of strategies for validation presented by Creswell and Poth (2018). Throughout the coding process, the authors met to discuss coding and debrief about the process. These discussions arose both with the two authors as they were coding, as well as with the entire group of authors. Additionally, to gain feedback and audit our work, we regularly discussed our progress within a larger group meeting to gain feedback from others who were outside the coding process but familiar with the research project. Our themes developed based on evidence in the data, including negative cases. We spend significant time engaging with the data throughout our prolonged analysis (3 months). In addition to being involved in the development of the unit and discussion with the authors during the professional development, the participant was also available to communicate with us whenever we had questions. We worked to generate rich, thick descriptions of the data based both on examples from the transcripts as well as a variety of visual representations to display the extensive amount of data in a concise manner.

2.5.6 Limitations

In this case study, we examined the teaching practices of a single teacher. Although we purposefully selected this teacher because he had demonstrated effective teaching practices in other research, the findings are limited to the single case and are not generalizable beyond this case. Although Mr. Evans's students had previously demonstrated significant learning gains in science, mathematics, and engineering, his teacher talk is among many aspects that might affect student learning. Therefore, we do not make claims about individual student learning based on the teacher talk because we cannot directly link his teacher talk to individual student learning gains. Additionally, although Mr. Evans's pedagogies were effective for him and his students, each teacher is unique; therefore, different pedagogies may be more appropriate for different teachers in different contexts. We focused our analysis on Mr. Evans's talk so that we could provide deep insight into his talk. However, this approach has the limitation that it does not incorporate student responses to his talk. Therefore, in our results, we present examples of Mr. Evans's talk, not exemplar excerpts of student talk. Finally, although we used data from an extended period in Mr. Evans' class, observations in different units, classes, or settings for longer periods might have yielded different results.

2.6 Results

In this study, we found a variety of ways in which Mr. Evans used engineering talk in his teaching. To present this data, we organized the results into three major themes: engineering talk for curriculum enhancement, engineering talk as pedagogical strategies, and engineering talk to convey engineering practices. Engineering talk for curriculum enhancement included organization of lessons and unit and preservation of the context of the engineering challenge. Engineering talk as pedagogical strategies included integration of engineering both systematically and opportunistically throughout the unit, incorporation and expansion of student ideas and inputs, and communication through teamwork. Engineering talk to convey engineering practices included reiteration of the client's problem and consideration of ethics and ISI. Although we coded all talk during whole-class verbal interactions, including both teacher and student talk, our research question focuses primarily on how Mr. Evans used his engineering talk, rather than the structure of the talk or how he prompted student responses. Therefore, the majority of the examples included in this section encompass quotes from Mr. Evans, with just enough student input to understand what Mr. Evans was saying.

2.6.1 Engineering Talk for Curriculum Enhancement

Engineering talk organized lessons and unit logically and aligned with engineering design process.

Mr. Evans used his engineering talk to lead organized and logical classroom verbal interactions. His lessons had an overall flow that guided student thinking to stay on task and to bring in necessary pieces of information as needed. To do this, Mr. Evans's verbal interactions with his students often focused on one area of engineering for a period of time with occasional short instances in other areas. The longer, focal interactions tended to be the major learning objectives of the lesson, whereas the short instances tended to highlight aspects of engineering such as considering the client, criteria, or problem context. The layout of two example lessons can be seen in Figure 2-3.

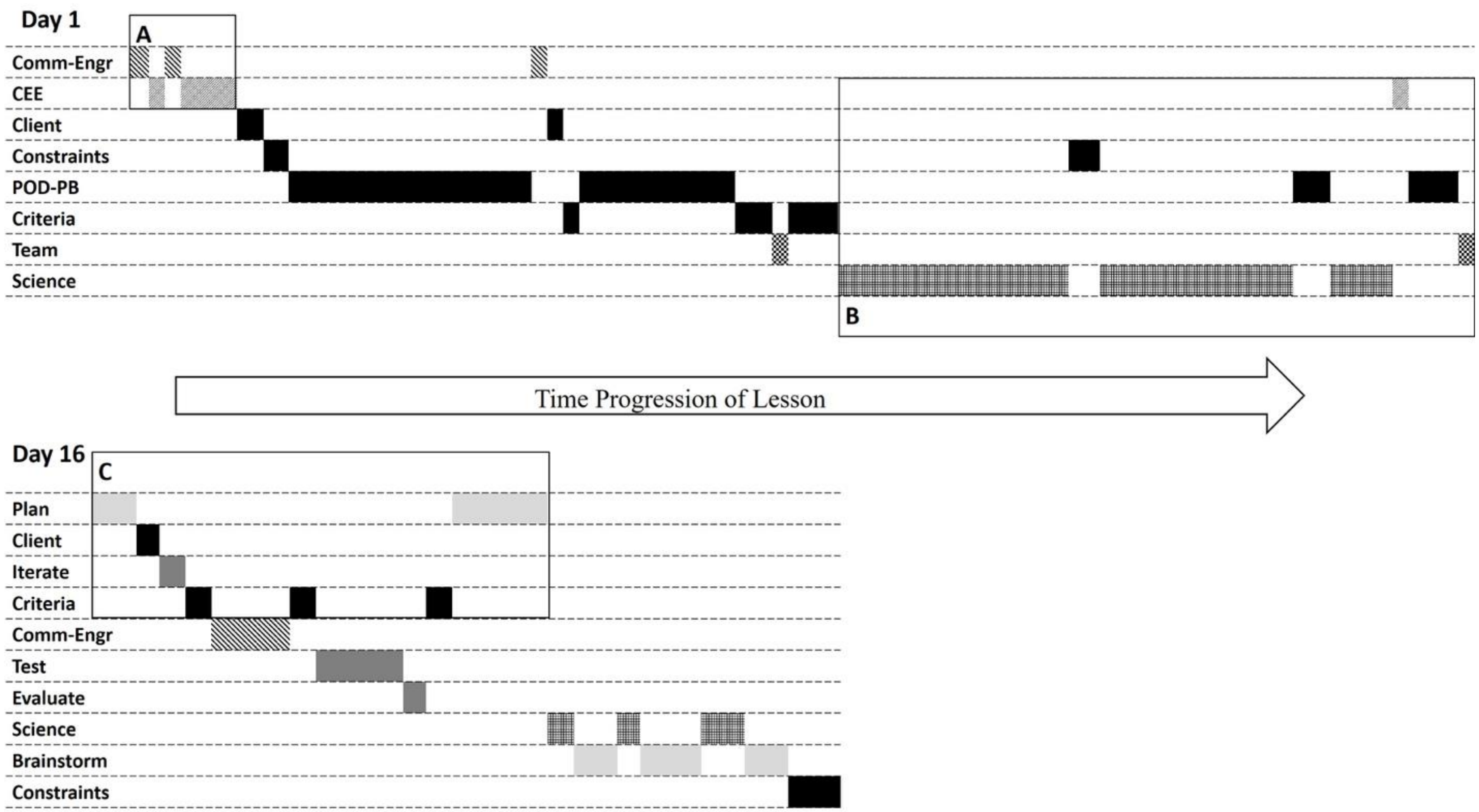

Figure 2-3. Layout of two example days: Day 1 and Day 16.

This figure illustrates how Mr. Evans organized his lessons. The length of transcript that Mr. Evans or his students talked about each indicator is represented by the width of the boxes. Moving down and to the right shows the time progression of the lesson. Solid shading represents the indicators that encompass the stages of the engineering design process. Each of the design process indicators and its subcodes are a different solid color: black for POD-PB and its subcodes, dark gray for POD-PI and its subcodes, and light gray for POD-TE and its subcodes. Hatched shading represents other indicators in the framework. Inserts a–c represent examples of how Mr. Evans uses an iterative process to bounce between integrated indicators. POD-PB, problem and background; POD-PI, plan and implement; POD-TE, test and evaluate

In Mr. Evans's whole-class verbal interactions, he stayed on each topic for a period of time, switched briefly to discuss one or two other things related to the topic, and returned to the first topic. For example, in Insert C in Figure 2-3, he began his verbal interaction with Plan. He then went into several topics students would need to consider during planning, such as Criteria and Test, before returning to Plan. In Insert A, he switched between communication (Comm-Engr) and conceptions of engineers and engineering (CEE) at the start of the lesson. Later, he switched between science and several aspects of engineering, including constraints and problem/background (POD-PB). These patterns helped structure the lessons, supporting students' thinking about different aspects of engineering and their iterative relationships. Although Mr. Evans only brought up a few indicators in each lesson, he did so in a purposeful way spending most of his time on indicators related to the learning objectives and bringing in additional, relevant engineering ideas in small increments with repetition.

In addition to following a meaningful structure on an individual lesson scale, Mr. Evans organized his engineering talk throughout the unit, as shown in the logical structures and processes of his lessons. This is shown in Figure 2-4 which displays the total amount (quantified by number of transcript lines) that he talked about each indicator in each lesson.

Indicators of Engineering	Day 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
POD-PB	76		16	3	29	8		14	17	9	7	17	15	5	17			
Client	3				3			2							4	2		
Constraints	9														3	6		
Criteria	17															20		
POD-PI																		
Brainstorm													8	7	2	17		
Plan										5			3		11	16		
Implement															5			
POD-TE																	4	
Iterative																3		
Test															5	10	7	
Evaluate																2		
SEM																		
Mathematics											37		10	174				
Science	72		45	256	39	135	23	333	322	130	283	117	3		3	9		
CEE	12		6		4	5									8			
Etools										6		68	8					
ISI		28	103								2		10		8			
Ethics			124															
Team	3	15	29	12		5			4	4		3			4			3
Comm-Engr	6				6	2					12		5	4	20	9	2	14

Figure 2-4. Total talk for each indicator on each day.

Values represent the number of lines of transcript that Mr. Evans talked about each indicator. Darker shading represents higher amounts of talk for each indicator.

Figure 2-4 demonstrates that the amount of time Mr. Evans spent talking to his whole class varied throughout the unit. For example, day 7 had limited whole-class verbal interactions because this was the second day of the DNA extraction lab. The students had background information from the previous day and needed minimal instruction to continue working, spending most of their time engaged in the DNA extraction. Additionally, on days when Mr. Evans was transitioning between topics, there was more variety of types of talk. For example, day 13 included a transition from science-focused lessons to mathematics-focused lessons, and day 15 involved a shift from planning to constructing the solution. On these days, Mr. Evans talked about a wider variety of indicators, to bring together multiple ideas and integrate them together. On Day 2, there was a camera malfunction and the first fifteen minutes of the class period were not recorded. However, from the field notes, we know that during this time Mr. Evans discussed the engineering notebooks and the logistics of organizing their notebooks, reviewed the information the students learned yesterday, including talking about who the client is and what the client wants, and introduced the debate.

As shown in Figure 2-4, Mr. Evans spent the majority of his talk on science. This corresponds with the objectives of the unit, because the unit aimed to have students learn science concepts and apply them to the engineering challenge. Additionally, science talk is not broken into sub-codes in the way that engineering talk is. Mathematics and technology talk were not as well represented as science. Therefore, Mr. Evans did not integrate mathematics and technology as much as science and engineering. It is important to note that as Mr. Evans is a science teacher, he was most comfortable with the science content and was expected to cover science standards.

The process of Mr. Evans's engineering talk follows the engineering design process. Figure 2-4 displays that Mr. Evans often discussed problem scoping aspects of design. As the students progressed through the design, he talked more about later stages of the engineering design process, especially brainstorming, planning, and testing. During the later lessons, especially days 17 and 18, Mr. Evans talked less to the whole class because the students spent most of the class periods working on their design. Throughout the unit, Mr. Evans used his engineering talk in a logical process that followed the engineering design process. He used an iterative process to move between indicators, following the engineering design process and frequently bringing up problem scoping.

Engineering talk preserved context of the engineering challenge.

Mr. Evans situated activities in the real-world context of the problem. He treated the problem as a real problem that the client was counting on them to solve, not just a classroom exercise. Mr. Evans began this theme at the beginning of the unit, introducing the unit with:

> The next several weeks you are going to be acting as engineers as we face another challenge posed to us. We'll be working with the [University] like we kind of did with the space plants. They were kind of our communication to NASA. We're lucky that the [University] likes to work with us.

Immediately, Mr. Evans set up his students to understand that they had been given a challenge, were working with the university, and their work was valuable. He explained that they were working *with* the university on a challenging problem that required the students to do the work of engineers.

> We are going to start our study of DNA so that we can get a better understanding of how GMO's work so we can begin to think about how we can address this problem of cross pollination of GMO's and non-GMO's.

Throughout the unit, Mr. Evans continued to treat his students like apprentice engineers and held high expectations that they would be able to do the work of engineers. For example, on day 5, leading up to talk about DNA, Mr. Evans reminded them what is expected of an engineer and connecting these conceptions to the challenge:

> Remember, as an engineer, it's not just utilizing one discipline, okay? As an engineer, you're going to have to use math, you're going to have to use science, okay? You're going to have to use a lot of different skills. So, as we start thinking about our client's concern, our client's desire to help prevent cross-contamination, cross-pollination of GMO and non-GMO plants, we need to start forming a good understanding of just exactly how that happens.

Mr. Evans told his students that they were working as engineers and used this as the reason why they needed to learn the different skills in the unit. He talked about the different disciplines, mathematics and science, that they would need to draw on to solve their client’s problem. Mr. Evans's preservation of the context of the engineering challenge gave his students a reason behind what they are doing and conveyed the idea that he thought of them as engineers.

2.6.2 Engineering Talk as Pedagogical Strategies

Engineering talk integrated engineering both systematically and opportunistically throughout the unit.

Mr. Evans used his engineering talk to integrate engineering with the science and mathematics content. He did this systematically on a large scale in many lessons by framing the lessons around understanding the problem, background, and client’s needs. He also integrated engineering opportunistically on a smaller scale by incorporating engineering ideas into many of the verbal interactions he led and taking advantage of teachable moments.

Almost every day, Mr. Evans systematically framed the lesson around the need to understand the problem in sufficient depth, instances coded as POD-PB. He also started and concluded most whole-class verbal interactions with a reminder of the problem or a reference to the client's needs. For example, on day 4, when introducing the topic of DNA, Mr. Evans told his class:

> We are going to start our study of DNA so that we can get a better understanding of how GMOs work so we can begin to think about how we can address this problem of cross pollinations of GMO's and non-GMO's.

In this example, he reminded his students that they were learning about DNA within the larger context of solving a problem and that the problem was specifically about cross pollination of GMO plants and non-GMO plants.

Mr. Evans used short references like this throughout his teaching. In another example, on day 9, focused on asexual versus sexual reproduction, Mr. Evans and his students had the following dialogue:

Mr. Evans:	If corn plants reproduce asexually, if corn plants did not reproduce sexually, would our GMO farmers and non-GMO farmers have a problem?
Many Students:	No.
Mr. Evans:	Raise your hand and explain to me why. [Student 1]?
Student 1:	Because then the corn would not go onto the non-GMO plant from the GMO plants, so then they wouldn't reproduce, like cross-pollinating.

Although brief, these points helped students understand the purpose of learning about asexual and sexual reproduction in the larger context of understanding and solving the problem. Mr. Evans returned to this idea the next day (day 10), while concluding the lesson focused on asexual versus sexual reproduction, Mr. Evans told his class:

> Remember the focus is what's going on with the DNA, and that's the biggest focus on what is the different sexual and asexual reproduction. DNA's the focus because we know that GMOs are determined by DNA, and so once we understand the reproductive strategies, that can help us understand our client's concern with the word cross-pollination, which as we know is a sexual reproduction strategy.

Again, he brought up the client and reminded the students that the reason they were learning about DNA and reproduction was to help them understand their client's concern. He not only tied the science lessons together with earlier lessons but also with the overall unit and engineering challenge.

Mr. Evans used similar instances to systematically intertwine and integrate the engineering challenge to provide context for his students. This trend of integrating the problem can be seen in the overall flow of many of Mr. Evans's lessons. Figure 2-5 displays the length (quantified by number of lines of transcript) and the order of each talk indicator on three example days from different points in the unit.

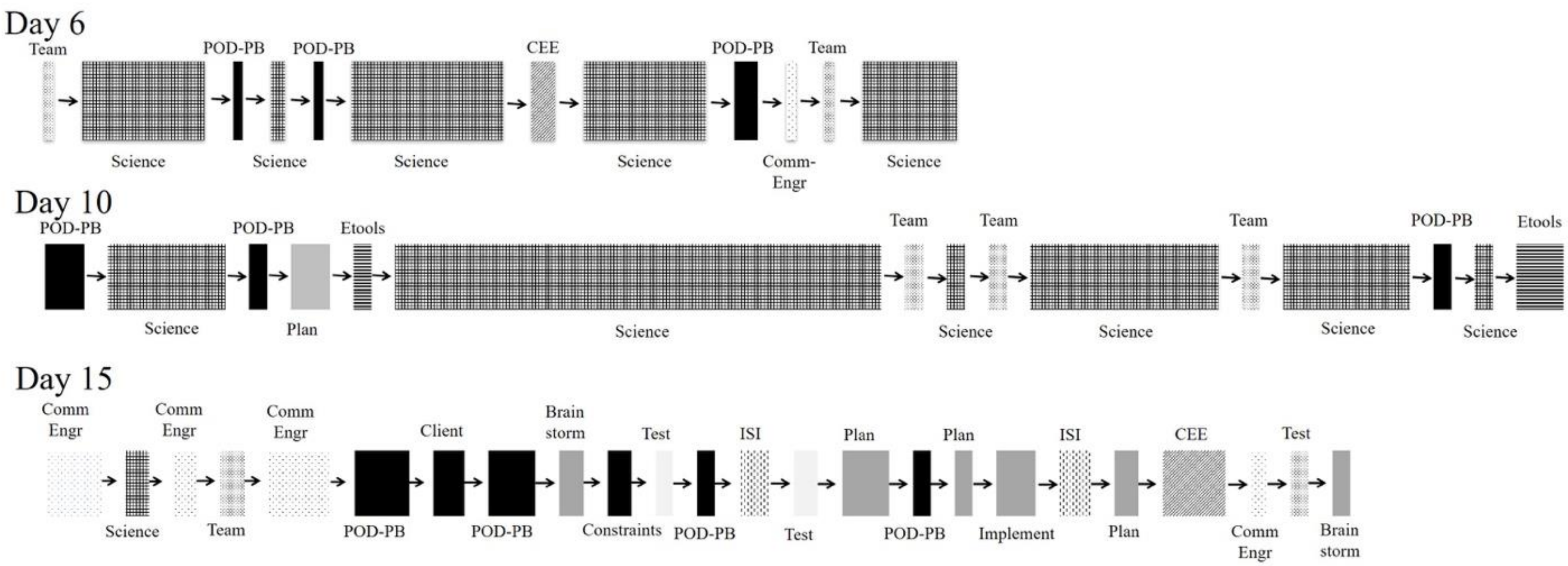

Figure 2-5. Layout of three example days: Days 6, 10, and 15

Illustrating examples of the time spent and the order of Mr. Evans's engineering talk. The length of transcript for each indicator that Mr. Evans or his students talked is represented by the width of the boxes. Each of the design process indicators and its subcodes are a different solid color: black for POD-PB and its subcodes, dark gray for POD-PI and its subcodes, and light gray for POD-TE and its subcodes. Hatched shading represents other indicators in the framework. PODPB, problem and background; POD-PI, plan and implement; POD-TE, test and evaluate.

Figure 2-5 demonstrates that Mr. Evans made multiple references to aspects of engineering within his science-based talk. For example, on both days 6 and 10, he discussed the Problem and Background (POD-PB) several times. Although these references were relatively short in the context of the entire scope of the whole-class verbal interactions, they helped to situate the learning and frame the lesson. On day 15, Mr. Evans continued to bring up POD-PB to remind his students of the context and problem, but also included later stages of the engineering design process, including Plan and Brainstorm, as his students were further along in the challenge and were considering other stages of the design process. Additionally, he included other aspects of engineering, such as communication (Comm-Engr), conceptions of engineering (CEE), and Teamwork, throughout the lessons, integrating the many aspects of engineering. Mr. Evans did this throughout the unit, as represented in Figure 2-4.

In addition to framing whole-class verbal interactions around the engineering problem, Mr. Evans also opportunistically integrated the science, mathematics, and engineering together instead of keeping the ideas separate. For example, Mr. Evans had the following interaction with his students integrating brainstorming with science content on day 16 (the instances coded as brainstorm are underlined and *science* are italicized):

Mr. Evans: *Remember what crops need*. Raise your hand and tell me. What do they need? [Student 2], what's one thing?

Student 2: *Water.*

Mr. Evans: *They need water*. Guys, if you build a big dome, and this is somebody's private farm, it's not a big corporate farm, and they don't have an irrigation system, where do they get water from? Rain. If you build a big dome around it and seal these crops off and they don't have access to rain, boom, the crops are going to die. That gives you a big score of zeros [on the evaluation rubric], all right? What else [Student 3]?

Student 3: *Energy or sun.*

Mr. Evans: Sunlight right, so if you, even in the case it is inside of some sort of, you know, substance and they can't even get through, I mean, think about that. But also if you're thinking the farmer is going to build up a wall made out of bricks or something okay, depending on what direction that field is facing, if the sun is for the last four hours of the day, sort of hitting that brick wall instead of hitting the crops behind the brick wall those crops that are in that shadow of the brick wall might struggle a little, right? So you're going to have to evaluate that they want all their crops to survive, *So think about the needs of the plants, so we said sunlight, we said water, and obviously it needs* *nutrients in the soil. You're probably not going to be messing too much with the soil, I want to think*. What else? [Student 4]?

Student 4: *Carbon-dioxide.*

Mr. Evans: *Carbon-dioxide and, of course, last but not least oxygen, okay. So plants need all these things* if you are messing with either any of those things, realize that that's probably going to give you, you know you might have a great barrier, but a bunch of dead crops aren't really helpful, right?

Mr. Evans incorporated brainstorming ideas and prompted his students to think about how the needs of plants and the science they were learning would affect their design. It is important to note that this example only incorporated short, monologic student responses. This example was chosen to concisely demonstrate Mr. Evans's abilities to weave together science and brainstorming.

The ways in which Mr. Evans intertwined and integrated the engineering challenge both systematically and opportunistically provided focus for his students. He integrated engineering throughout the lessons using strategies such as framing the lessons around POD-PB and integrating engineering topics into science-focused talk.

Teacher engineering talk incorporated and expanded of student inputs and ideas.

Based on the examples of how Mr. Evans integrated engineering ideas into his whole-class verbal interactions, we found that Mr. Evans not only treated his students as young engineers but also used his students' ideas as a starting place for engineering talk. For example, on day 13 when students were beginning to plan, a student asked, "Why couldn't they have just put a big brick wall in the first place?" Mr. Evans responded with:

> That's a good thought. Maybe that's what your solution is going to be, but you're going to want to think back to some of the client's needs, and you have your engineer's notebook for that, about the ease of implementation and all these other things to think about. Then, there are also things to think about with sort of just the natural needs of a crop field, right? Without saying much more than that I want you guys to kind of work through some of that, but there is nothing that says that can't be your proposal. If you want to put a big brick wall there maybe that's what you're going to go for.

Here, he reminded the students of the client's needs, the criteria and constraints that they needed to consider, and the science they needed to think about, particularly the needs of the crops. He acknowledged the student's idea and used it as a starting place to bring up different aspects to consider before choosing a design. After this comment, he continued with the discussion from before the student's question. However, the next day, when the students were about to begin work in their teams, he returned to the student's question:

> Before you think, "I'm just going to put up a big brick wall, nothing's going to get by it." Think about how that might impact crop growth, the needs of those crops, and why [because of] those things, that might not be the best course of action. What you should be doing is either brainstorming your barrier, some ideas, and a whole bunch of supplies that we can use. You're not going to start using them today; you're not building today.

He used a student's idea to remind the students of important considerations in an engineering project. He also implied the iterative nature of the design process by revisiting ideas and building on them with new knowledge. By incorporating students' ideas in his talk and expanding on them at teachable moments, Mr. Evans developed a classroom atmosphere that encouraged his students to propose ideas and consider their effects.

Teacher engineering talk established communication and teamwork skills.

Most instances that were coded as Team entailed Mr. Evans giving instructions about what students should be doing with their teams and tips on how to work together. Instances of teamwork were often closely aligned to communication because communicating with their teammates was a major component of the unit, in addition to communication with their client and teacher in the form of letters and notebooks. For example, on day 1, Mr. Evans told his class:

> You should also at this point sort of get to know your group a little and find out what each of you already know or think you already know, right, and we'll address those things

On day 18 he said:

> With your groups today, when you have time, maybe you're waiting in line to test or whatever, you're done testing, if you want to work with your group, write down your argument for the client, bringing in evidence from your testing.

In both these examples, he was providing support for teamwork. In the examples, from both the beginning and end of the unit, he gives his students a goal and a deliverable they will need to produce with their team, either something to communicate to the whole class or through a letter to their client. Throughout the unit, he gave similar suggestions to guide his students in their teamwork and facilitate their collaboration.

In addition to giving students guidance on how to work and communicate with their teammates, Mr. Evans also addressed other aspects of communication in engineering in similar ways. Much of his communication advice consisted of how and when to record things in their notebooks so that they had access to vital information. For example, on day 15, Mr. Evans told his class, “I encourage you, between now and next Tuesday, as we're working on our prototypes and our testing, make sure you take the time to write things in your notebook.” In this example, he reiterated the importance of maintaining their engineering notebooks. Mr. Evans also interspersed advice about how to communicate with and persuade their client that their solution was the best. For example, he advised, “the bias in the persuasion is important, but you also want to use evidence from your design, from your testing, and base it upon the client’s requests.” Here, Mr. Evans gave his students advice about how to write a persuasive and informative letter to their client.

Mr. Evans encouraged teamwork and communication by giving specific instructions and tips for teamwork and communication. He addressed different aspects of communication, including how to record their ideas in their engineering notebooks, communicate with their teammates, and work with their client.

2.6.3 Engineering Talk to Convey Engineering Practices

Engineering talk reiterated client’s problem.

Mr. Evans used a significant amount of his engineering talk to reiterate the need to focus on the client’s problem and how the unit’s activities would help them solve their client’s problem. For example, on day 15 he said, “What I want you to do to start with is brainstorm with the group. Sketch some ideas. Think about how it might impact the crops. Think about the needs of our client.” Here, Mr. Evans situated the task around the client’s problem, reminding the students what they should be doing and giving them a reason why. On day 12, the final science lesson, Mr. Evans told the class:

> We're getting to the end of our gathering knowledge part, because we're going to be, this week, working to [develop] the solution to our client's problem. We understand GMOs, we understand sexual reproduction, we understand asexual reproduction, we understand how things are inherited, one from mom, one from dad. We've looked at alleles. We've talked about Punnett squares and things. We'll do a little more practice with that. We have the big picture here. Corn plants reproduce sexually and so the pollen from a GMO plant is carrying the GMO gene, which can then fertilize a non-GMO plant. You end up having a GMO offspring

from that. This is the last final step in understanding this process. How does the actual GMO get made? Your job, for our clients, is not to stop GMOs from being made. We're not going in trying to interrupt this process. Our job is to help non-GMO farmers keep their plants isolated or avoid fertilization from a GMO plant. It's good to understand the process as well.

Although relativity brief, he reminded his students of what they had learned and why they needed to learn these topics, integrating the science with the engineering challenge set forth by the client. He used the client's problem to give a short summary of the key ideas and how this related to the overall problem.

Engineering talk on ethics and ISI.

Mr. Evans used his talk about ethics, current issues, and how solutions potentially impact people to engage students in the real-world context of GMOs and help the students see the complexity of the engineering design problem. Mr. Evans talked about ethics on day 3 leading up to and during the debate. During this debate, each team of students took on the role of a stakeholder in GMO regulation, including representatives from the Center for Food Safety, plants and biotechnology industry, organic farmers, general scientific community, and consumers. They were tasked to consider and support how GMO crops should be regulated, based on information they learned from reading an article. A major component of this debate was the ethics and impacts of the regulations they proposed. Therefore, near the beginning of the lesson, Mr. Evans asked his students for their ideas about ethics. After listening to student responses, Mr. Evans summed up their ideas by saying:

Mr. Evans: Morally right and wrong. Is it right or wrong? So even though you're going to be putting yourselves in the role of these biased groups [during the debate], consider also the ethics of the decisions you make. The people in these situations are real people... *[conversation about debate but not ethics]* ...But these are real people who probably do think about ethics and morals and so when you as a group are thinking about how you want to treat the sugar beets or how you want them regulated, think about the people you, maybe, that you might be impacting with these decision. Try to bring that in. [Student 5], what's up?

Student 5: What do they spray the stuff the sugar beets stick to? Is it still on the sugar beets?

Mr. Evans: The chemical?

Student 5: Yeah. Is it harmful?

Mr. Evans: That's kind of where we come into the question of the health considerations. I don't think there's necessarily a lot of health concern with GMOs in the sense of them being GMOs, but rather it's more related to the fact that in agriculture, a lot of GMOs are GMOs because they are designed to be resistant to chemicals. ... *[conversation about chemicals used but not ethics]* ... Are they harmful to humans? Is there a concentration high enough to even be a problem? That's where there's current research. I don't know that there's a set answer to that right now.

Here, Mr. Evans gave his students a short and simple definition of ethics before going into depth about ethical considerations that come into play. His talk about the effects of ethical considerations prompted a student to think of another ethical consideration and ask a question, which Mr. Evans in turn used to add more depth to his ethics talk. He demonstrated the complex nature of ethics by proposing further questions and explicitly stating that there are not always answers to these questions. He posed these questions in a way to prompt students' thinking and told them that people are actively researching and looking for answers.

Mr. Evans approached ISI similarly by using his talk to prompt student thinking about the issues surrounding their actions and decisions and as a bridge between the engineering problem and the science content. For example, on day 15, Mr. Evans told his class:

> Not only that [the material of the structure] but consider what impact a solid opaque structure might have on the crops on either side of it. Your number one task is to keep the pollen out but weigh those other conditions. Make sure that what you're doing isn't going to cause other more significant problems.

In this example, he started to make connections between what they were designing, how their decisions would affect the farmers' crops, and the criteria and constraints of the problem.

Although the instances of ethics and ISI that Mr. Evans used posed important questions and prompted student thinking, he did not emphasize them throughout the unit in the same way that he did with other indicators. Figure 2-4 highlights that ethics talk was limited to the lesson focused on the debate (day 3) and ISI talk was limited to only short instances on a few days. This suggests that Mr. Evans missed opportunities to bring back the ideas that were brought up in the debate to integrate ethics and ISI into the rest of the unit. However, because ethics is rarely explicitly integrated into pre-college engineering curriculum and instruction, it is significant that he discussed ethics and implications with his students and wrote the curriculum with a context that allowed meaningful discussion of ethics.

2.7 Discussion

This study investigated the engineering talk of a middle school life-science teacher during an engineering design-based integrated STEM unit. We focused on the teacher's talk during whole-class verbal interactions with the purpose of better understanding how the teacher used engineering talk to frame the classroom and convey information to his students. Although this approach does not allow us to draw conclusions that correlate student learning to the teacher's talk, it does provide insights into how the teacher used engineering talk in his classroom in a number of positive ways. Specifically, our analysis showed that the teacher in this study acted as an informed engineering designer and talked with his students in a way that mirrored these practices. He also used his talk to integrate science, mathematics, engineering, and technology, treat students as engineers, and maintain the context of the problem.

2.7.1 Integrating Science, Mathematics, and Engineering through Engineering Talk

Successful STEM integration relies on the effective instruction of each individual subject as well as their integration. Mr. Evans used his engineering talk as a method to integrate the subjects, allowing his students to fully benefit from the many advantages of STEM integration, which include increasing student engagement, improving student learning, and providing a meaningful way to teach science and mathematics (Cantrell et al., 2006; Sanders, 2008). Mr. Evans used a variety of strategies in his engineering talk to achieve this integration. For example, he framed the science-focused lessons around the engineering design challenge and often reminded students how the science and mathematics they were learning would help them to develop their solution. Additionally, when students proposed solutions to the engineering challenge, he built on their ideas to reiterate science concepts and encouraged his students to think about what they still needed to learn. By doing this, Mr. Evans helped his students apply ideas from one discipline to another and purposefully integrated the subjects together. Mr. Evans's instruction benefited from the way the curriculum was written, in a way that incorporated the science into the engineering challenge. However, he used engineering talk above and beyond what was written in the curriculum to successfully integrate the subjects. It is often a struggle for elementary and middle school teachers to meaningfully integrate science with engineering in a way that requires the students to learn the science (Capobianco & Rupp, 2014; Wendell et al., 2014). Therefore, Mr. Evans' methods have potential to better support this integration. Additionally, Mr. Evans's method of integrating engineering throughout the unit, rather than focusing engineering at the end of the unit in a culminating project, may have increased his students' motivation and learning of engineering (Guzey, Moore, & Morse, 2016; Guzey, Moore, Harwell, et al., 2016).

Mr. Evans integrated more science talk into his lessons than mathematics talk. However, because Mr. Evans is a science teacher, he has more experience with science talk and he is accountable to science standards. Therefore, it is important to note the struggle to balance the many aspects of STEM integration effectively. The technology aspects of STEM integration came into play mainly through the engineering talk coded as ETools and through the students' creation of their design, which is itself a technology. By integrating science, mathematics, and engineering through engineering talk, Mr. Evans demonstrated engineering as an integrator (Guzey, Moore, & Morse, 2016; Guzey, Moore, Harwell, et al., 2016), used NGSS practices effectively (NGSS Lead States, 2013), and enacted his definition of STEM for his classroom's educational purposes – providing evidence that he overcame the challenge of defining STEM set out by Bybee (2013).

2.7.2 Modeling Informed Design Practices through Engineering Talk

Mr. Evans used his talk to model practices of informed designers. He talked his students through the engineering design process and engineering practices to help them think about the problem as engineers and guide them towards a holistic understanding of engineering. He did this not only by guiding his students through the engineering design process, but also demonstrated other engineering practices, such as incorporating the iterative nature of engineering design, directly addressing conceptions of engineers and engineering, and helping his students balance multiple ideas as they developed their solution.

A key way that Mr. Evans guided his students through engineering design was by using his engineering talk to model the engineering design process. He focused mostly on problem scoping on the first day, learning background information on the following days, followed by planning and brainstorming, and then testing and evaluating in the subsequent days. Mr. Evans spent significant time on problem scoping, including talk about the client and problem. Mr. Evans guided his students through the process of learning background information and encouraged his students to spend time on problem scoping, directly tackling major challenges for his students as novice designers (Atman et al., 2007; Crismond & Adams, 2012; Watkins et al., 2014). As teachers are often more comfortable with the later stages of the engineering design process (Hynes, 2010), these results suggest ways that teachers can incorporate problem scoping when teaching engineering design.

As students progressed through the unit and moved towards completion of their engineering challenge, Mr. Evans incorporated more and more of the later stages of the engineering design process. For example, later in the unit, he talked more about planning and implementing. He did not discuss testing and evaluating until the final days, when students were engaged in testing and evaluating their solution. This progression follows patterns that experts use in their engineering design. For example, when Atman et al. (2007) compared student and expert designers, the experts focused on problem scoping and gathering information for a significant amount of time and evaluating the solution only towards the end of their process, allowing them to balance multiple ideas before using their tests to eliminate design ideas.

Mr. Evans emphasized the iterative nature of engineering design and encouraged his students to think of engineering design as an iterative process and modeled how to think iteratively. For example, he did this explicitly by talking to his students about the need to continuously reconsider the needs of the client and the problem they were solving. Additionally, the overall flow of his talk mimicked the iterative nature of design because, while using engineering talk, he bounced back and forth between topics to consider different aspects of the problem and the relationship between the science and engineering the students were learning. Being able to be iterative throughout problem solving and design is a key skill of informed designers that is not present in novices (Crismond & Adams, 2012; Daly et al., 2012; Dym et al., 2005).

In addition to problem scoping, the engineering design process, and the iterative nature of design, Mr. Evans incorporated many other practices of informed designers through his engineering talk. For example, informed designers balance multiple ideas and consider the tradeoffs of different designs (Crismond & Adams, 2012; Kolko, 2010). One way that Mr. Evans modeled this was by taking a student's idea and suggesting they continue to consider it, while learning and thinking about other ideas so that they would be able to balance and consider multiple aspects of the design. He also proposed how different aspects of the science they were learning would affect different ideas the students had brainstormed. Another aspect of engineering design that Mr. Evans modeled for his students was representing their ideas in multiple ways (Crismond & Adams, 2012; Gainsburg et al., 2016). Mr. Evans did this by telling his students what to write in their notebooks at certain times and how to represent their ideas so their teammates and the client could understand. Overall, Mr. Evans guided his students through the engineering challenge by telling them what to do at certain points and how to do these things in ways that helped them to practice the actions of more informed designers. By modeling informed design practices through engineering talk, Mr. Evans demonstrated that, in his classroom, he actively integrates technology and engineering (Bybee, 2013) through required practices from NGSS (NGSS Lead States, 2013) and more comprehensive engineering practices (Crawley et al., 2014) that go beyond academic standards.

2.7.3 Leveraging Engineering Context

Mr. Evans presented this unit in a context that he, and the team he worked with to develop the unit, chose to be meaningful to his students and maintained the context throughout the unit. There were aspects explicitly written into the curriculum with the aim of making the context meaningful to students, such as including a client and situating the challenge within a context that was relatable to his students. Mr. Evans capitalized on these aspects of the curriculum, but also went beyond them to use his talk to maintain the context and purpose of the unit. For example, he often reminded the students of the client they were working for and the needs of their client, helping students to see the purpose of their work beyond the classroom. This emphasis may have contributed to his efforts to give his students motivation to solve engineering problems (Cunningham & Lachapelle, 2014; Ganesh & Schnittka, 2014; Prins et al., 2016).

In addition to maintaining the overall context of the unit, the teacher also maintained his treatment of his students as engineers. Mr. Evans referred to his students as engineers that are working on a problem, with phrases such as, “as engineers, you need to…,” instead of treating them as students involved in a required classroom unit. Additionally, he presented the skills the students needed, such as understanding sexual reproduction, in the context of the engineering challenge. He made it clear to his students that they needed to learn these concepts to understand and meet the needs of their client. Another way he used his talk to give opportunities to practice being engineers was through communication and teamwork. He gave his students specific instructions on how to better work with their teams and communicate their ideas. Communication and teamwork are skills that students need to learn and practice to do effectively (Dym et al., 2005; Moore, Glancy, et al., 2014) and treating his students like engineers gave them a reason to practice these skills in an engaging context. Treating students as engineers not only helps them to develop skills in engineering, but also helps to develop their identities as problem solvers and potential future engineers (Cunningham & Lachapelle, 2014; Lindsay et al., 2008). Students with stronger engineering identities are more likely to pursue and persist in engineering (Tonso, 2014). Because many students have incomplete conceptions of what engineers do and who engineers are (Capobianco et al., 2011; Pantoya et al., 2015), treating all students as engineers may help them overcome their stereotypes to think of themselves as engineers and be better able to integrate the practices of engineers with the technical aspects of engineering (Lindsay et al., 2008). Teachers are one of the top influences on students' beliefs about their abilities in STEM, especially for female students (Fouad et al., 2010; Guerra & Lim, 2017); therefore, if students have teachers who treat them as engineers, they will have more positive beliefs about their abilities in engineering.

Engineering ethics are an important aspect of acting like engineers. To gain a picture of the complex nature of engineering ethics, students need multiple and varied experiences with the practices of engineering (Moore et al., 2015). Mr. Evans only discussed ethics on one day and ethics were not integrated in the same way as many other aspects of engineering. For example, he could have used the ethical dilemmas that arose in the ethics debate as another way to help his students continue to think about stakeholders in design. Ethics integration might have been more difficult for the teacher because he is less comfortable with teaching the ethics of engineering or because the curriculum was not written to emphasize these aspects. It is often a challenge for teachers to integrate meaningful ethics into their classrooms (Sadler et al., 2006), so the fact that Mr. Evans included ethics in his curriculum and teaching is commendable. However, the missed opportunities to use the ethical dilemmas uncovered during the debate suggest that there are integrative pedagogies using ethics as the thread that need to be further explored. Mr. Evans leveraged the engineering context (Bybee, 2013) – both the context of the engineering challenge and the context of his students being engineers, to give students purpose for learning the science and relevant mathematics content he had set out for them and provided them with a well-rounded engineering education experience.

2.8 Conclusions and Implications

This study explicitly lays out how a middle school science teacher used engineering talk in an engineering design-based STEM integration unit. Mr. Evans's teaching practice with engineering talk provides insight into how to enact the excellent engineering practices called for in the NGSS. Furthermore, he goes beyond the NGSS standards and practices to introduce his students to what engineering is and how engineers solve problems by including additional engineering practices such as teamwork and ethical thinking. He used engineering talk to integrate science, mathematics, and engineering concepts throughout the entirety of the unit by framing lessons around the engineering design problem to remind students of the rationale for learning content matter. He built on students' ideas to address connections between STEM subjects and modeled informed design in engineering by paralleling the design process of informed designers while continually bringing up the client's problem. His talk emphasized the iterative nature of design by strategically bouncing back and forth between topics to bring up ideas as they were needed. He explicitly instructed his students how to use their communication skills, including notebooking and team interactions, and talked them through the process of balancing multiple ideas for their design solution. Mr. Evans engaged his students as engineers and maintained a context for the design challenge that he felt was motivating for his students. Together these ways of using engineering talk provide evidence that a single teacher in one unit can overcome the three challenges to STEM education in teacher practice set out by Bybee (2013): (1) actively integrate technology and engineering, (2) use STEM-related contexts as a means to education students in STEM disciplines, and (3) define STEM for classroom purposes.

These findings have the potential to improve aspects of teaching that are unique to engineering design by increasing knowledge of what engineering design pedagogies look like at the middle school level. Collectively, Mr. Evans's talk strategies provided interconnected examples of effective engineering talk. However, even particular strategies that he used have the potential to be more easily implemented into a teacher's talk, such as his habit of often giving short reminders to students of why they were doing each task in the context of the larger engineering project or how to practice certain strategies, such as using evidence in their explanations and recording ideas in their notebooks. This study also supports and extends previous research on the importance of the role of engineering for integration of science and mathematics at middle school level. Mr. Evans integrated science talk much more than mathematics or technology, which reflects his greater level of experience teaching science. This highlights the challenge of integrating multiple and unfamiliar disciplines into a single classroom and points to areas of further research to better understand how to support teachers' integration of all STEM disciplines. Additionally, further research should address the effectiveness of these pedagogies to improve student learning and motivation and the pedagogical content knowledge needed to enact these pedagogies. Future work should also address how engineering talk aligns with other pedagogical strategies used during engineering design-based instruction as well as the student perspective and interpretation on teacher talk.

2.9 Acknowledgements

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RE: JEE-2017-0277.R3

Lisa Benson <lbenson@clemson.edu>
Mon 4/29/2019 10:09 AM
To: Amanda Johnston <johnst78@purdue.edu>; Barbara Ramirez <bjram@clemson.edu>

Amanda –

Thank you for these files. There is not a conflict in terms of copyright for your dissertation.

Lisa

From: Amanda Johnston <johnst78@purdue.edu>
Sent: Monday, April 29, 2019 11:26 AM
To: Barbara Ramirez <bjram@clemson.edu>
Cc: Lisa Benson <lbenson@clemson.edu>
Subject: Re: JEE-2017-0277.R3

Hello Dr. Ramirez,

Attached is a copy of our final manuscript. We have unblinded it and made the changes suggested by the Associate Editor and Editor. We were able to shorten the manuscript by about 800 words, but could not find other areas to cut without changing the meanings that the reviewers had asked for. We are able to pay the page charges for the manuscript.

I am planning to use this manuscript as part of my dissertation that will be completed next year. I just want to confirm that there will be no copyright issues after the manuscript has been published and that I will still be able to use it as part of my dissertation.

Thanks,
Amanda Johnston
PhD candidate
Engineering Education
Purdue University

From: Lisa Benson <onbehalfof@manuscriptcentral.com>
Sent: Wednesday, April 3, 2019 2:00 PM
To: Amanda Johnston
Cc: bjram@clemson.edu; terig@clemson.edu
Subject: JEE-2017-0277.R3

JOURNAL OF ENGINEERING EDUCATION
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03-Apr-2019

Re: "Engineering as the Integrator: A Case Study of One Middle School Science Teacher's Talk," JEE-2017-0277.R3

Dear Authors:

3. ENGINEERING CONVERSATIONS: TEACHER TALK DURING INTERACTIONS WITH TEAMS OF MIDDLE SCHOOL STUDENTS WORKING ON ENGINEERING DESIGN PROJECTS

Teaching engineering at the middle school level is "an ideal time to cultivate and enhance students' interests in STEM courses, careers, and activities" (Ganesh & Schnittka, 2014, p. 108). Engineering in middle school has been shown to decrease performance gaps and increase engagement in underrepresented groups (Cantrell et al., 2006; Guzey, Moore, Harwell, et al., 2016), start to overcome the misconceptions that students hold about engineers and engineering (Capobianco et al., 2011; Fralick et al., 2009), and reach a greater diversity of students, especially girls and underrepresented minorities who are less likely to continue in STEM courses in high school and beyond (Cunningham & Lachapelle, 2014). However, middle school students still need significant support to be successful in complex engineering problems and projects. Design is a social activity that requires an array of types of communication (Cross & Clayburn Cross, 1995; Ferriera et al., 2015). Middle school students do not have all the skills they need to independently and effectively work with teammates to learn new, complex ideas, and they need teacher support and scaffolding (Dawes, 2004). Although teachers set up many aspects of their classroom structure in whole class settings, a major way in which they support student learning is through their interactions with individual teams. This study examines these teacher-team interactions when middle school students are working on engineering design projects, addressing the research question: How do teachers use their talk to interact with teams of middle school students as they work on engineering design projects?

3.1 Background Literature

Middle school is an important time to engage students in engineering design learning to reach a diverse group of students and to prepare students for future success in engineering. The strategies teachers use to talk to their students about engineering design are important for setting up how students think about and learn engineering design.

3.1.1 Middle School Engineering

The middle school years are an essential time to engage students in authentic, positive engineering experiences in order to improve the diversity of students in engineering programs and better prepare these students for success in engineering (Buck & Ehlers, 2002; Cantrell et al., 2006). Many students make decisions about their future career paths and start to self-select out of STEM classes, and therefore careers, during middle school (Brophy et al., 2008). Additionally, at the middle school level, students are capable of engaging in authentic engineering, if they have effective support (English et al., 2013; Zhou et al., 2017), and engagement with engineering has been shown to improve both students' attitudes and knowledge of engineering and science (Guzey, Harwell, et al., 2017; Guzey, Moore, Harwell, et al., 2016). Therefore, high-quality engineering teaching during the middle school years is essential to reach more diverse students and increase their access to engineering as a career option.

There are several key goals and learning outcomes that have been identified for student engineering designers, especially at the middle school level (Moore, Glancy, et al., 2014). Among others, these goals include learning to use evidence to justify decisions, learning from failure, learning to apply science and mathematics content knowledge, balancing tradeoffs, working in teams, understanding ethics of engineering, and learning to problem scope (Barakat, 2011; Goldstein, 2018; Maltese et al., 2018; Marks & Chase, 2019; Mathis et al., 2016; Warshauer, 2015; Wendell et al., 2017). Additionally, in order to build identities as future engineers, it is important that students see connections to their lives and the potential for engineering to support their communities and the world (Kloser et al., 2018; Moore, Stohlmann, et al., 2014; Pantoya et al., 2015; Stevens et al., 2008). However, most middle school teachers do not have experience with engineering and therefore often lack the confidence to teach engineering (Hynes, 2010). There have been examples of effective professional development programs that have shown improvements in both understandings of engineering and confidence in teaching engineering in precollege teachers (Diefes-Dux, 2014; Duncan et al., 2011; Mesutoglu & Baran, 2020; Meyer, 2018). However, the effects of these programs, the longer term follow up, and the connections to student learning need further study (Daugherty, 2009; Daugherty & Custer, 2014; Soysal, 2018).

3.1.2 Teacher talk strategies

Prior research, primarily in science and mathematics education, has described many ways that teachers can use their talk to promote high-order thinking and engagement; thinking that is needed for authentic engineering design. For example, open-ended questioning, reflective questioning, focusing on conceptual understanding, linguistic linking concepts, talking about contexts, using a mix of informal and formal vocabulary, and asking students to explain their ideas have all been linked to higher level learning (Blown & Bryce, 2016; Bower, 2005; Keong et al., 2016; McNeill & Pimentel, 2010; Smart & Marshall, 2013; van Zee et al., 2001; van Zee & Minstrell, 1997). Additionally, when teachers use their talk to convey messages focused on the learning process rather than the "right answer", allow students to see that teachers are developing their own understandings along with the students, and model positive social messages, students themselves ask more questions of their peers, feel more empowered in their learning, and have higher learning gains (Cummings et al., 2015; Jung & McFadden, 2018; Pimentel & McNeill, 2013; Scott, 1998; van Zee & Minstrell, 1997).

There are added challenges to teacher talk when students are working in teams, because the teacher must support and model effective ways for the students to talk to each other. For example, Dawes (2004), in a study examining student and teacher talk interactions in science classrooms, identified four essential language tools that team members can employ to work effectively together to learn science. These are: (1) *talk awareness*, where "the teacher must be explicit about the high value of group talk," (p. 685) (2) *key questions and reasoning*, such as "What do you think?" and "Why do you think that?" (3) *active listening*, and (4) *joint decision-making*. If teachers model these types of talk and scaffold their students to also use them, students are better able to support each other and have more productive team learning experiences (Webb et al., 2009). Other strategies include "making reference to ground rules, focusing on [the] task, inviting [students] to speak, active listening, repeating relevant ideas expressed by students, probing and exploring students' understandings, encouraging students to compare and test ideas, [and] identifying resources for thinking" (Hofmann & Mercer, 2016, p. 412). Further strategies include "the use of long and interconnected utterances, the use of linguistic links between curricular content, the use of context as a motivator for the curricular content, the use of informal language for mathematical manipulations, and the use of an entertaining presentation style" (Bower, 2005, p. 164). In addition to these specific strategies, teachers also need to use their language "to encourage groups rather than individuals" to help students learn the value of teamwork (Dawes, 2004, p. 683).

To know how much support to give teams of students, teachers must use their interactions to formatively assess students and adapt what they say to meet the needs of their students and effectively scaffold their learning (Wood et al., 1976), which is difficult to accomplish (van de Pol et al., 2014). Teachers often initiate interactions with students and use their talk to elicit student ideas to formatively assess their students (Leung & Mohan, 2004; Ruiz-Primo & Furtak, 2006). Teachers need to "find out what children think and to organize ways of helping them to question their own ideas and those of others" (Dawes, 2004, p. 678). Questioning is often a strategy that teachers use to formatively assess students and better understand what students know or how they approach problems. For example, Cummings et al. (2015) found that in mechanical engineering design reviews, professors often asked questions that required students to defend their ideas or to explain how they had anticipated different parts of the problem. Additionally, instructors use their talk to model the types of things that students should think about to assess their own work (Oak & Lloyd, 2015).

Although much of the research from mathematics and science education on teacher talk is relevant and applicable to engineering education, there are aspects of engineering that set it apart from mathematics and science education that teachers need to address through what they say in the classroom. These unique aspects of engineering design are outlined in the theoretical framework, which sets up the definition of engineering design that is used to frame the analysis in this study. In order to understand the most effective ways for teachers to interact with their students, we need to understand what they actually say in the classroom and how their talk supports students.

3.2 Theoretical Framework

This study examines how teachers use their talk to interact with students during engineering design projects. This section outlines a definition of engineering design and the teacher's role in helping students learn engineering design, which was used to frame the analysis.

Design is a core practice of engineers, to the point where "design is often defined as synonymous with what engineers 'do'" (Daly, Adams, & Bodner, 2012, p. 187). For example, some authors use the terms engineering design and engineering interchangeably (Johnson, 2009; Petroski, 1996) because the two concepts are so interconnected. Additionally, a common measure of students' engineering literacy is their ability to apply the engineering design process to a new situation (Mentzer et al., 2015; Sneider & Purzer, 2014), and the ability to design is seen as a core outcome at all levels of engineering education (ABET, 2018; Froyd et al., 2012; NAE & NRC, 2009; NGSS Lead States, 2013).

However, design is challenging. Design problems are complex, ill-structured and have multiple solution paths (Daly et al., 2012; Gainsburg et al., 2016; Jonassen et al., 2006; Simon, 1969). They require use of technical and social skills, iterative processes, and limited resources (Johnson, 2009; Jonassen et al., 2006). Engineering designers must be able to balance trade-offs and competing criteria, use evidence to make decisions, consider multiple stakeholders, and apply knowledge from a vast range of disciplines (Atman et al., 2007; Daly et al., 2012; Dym et al., 2005; Jonassen et al., 2006; McKenna, 2007). For students and inexperienced designers, many of these factors are challenging. For example, beginning designers often treat design tasks as well-defined, skip doing research about the problem, quickly jump into solution generation, become fixated on an idea, make decisions without weighing evidence, and conduct few, non-analytical tests (Crismond & Adams, 2012).

However, in order to learn how to design, engineers and engineering students must practice design, including complex and ill-structured design projects that exist outside of their abilities to work by themselves. To help them succeed, a more knowledgeable other can provide scaffolding for their learning (Vygotsky, 1986; Wood et al., 1976; also e.g., Cohrssen, Church, & Tayler, 2014; Kawalkar & Vijapurkar, 2013; van de Pol, Volman, Oort, & Beishuizen, 2014). In the classroom, the teacher, in addition to more knowledgeable peers, act as the more knowledgeable other. Teachers provide scaffolding to their students through a variety of decisions in the classroom, including the instructional materials that they use, the structure of their classroom, and the complexity of problems that they choose to give to students. However, the ways in which teachers use their talk to interact with students is an essential aspect of scaffolding. The teachers actions of "explain[ing], suppl[ying] information, question[ing], correct[ing], and ma[king] the pupil explain" (Vygotsky, 1986, p. 191) allow the students to bridge their zone of proximal development to be able to understand concepts and solve problems that they could not do alone. The ways in which teachers talk to their students are essential for scaffolding many aspects of learning, such as how they think about problems, how and if they seek help, and how they use their own language (e.g., Fleming, 1998; Lemke, 1990; Nathan & Kim, 2009; Scott, 1998). The teachers' language also contributes to how the students continue to think about concepts after the teacher has withdrawn their support.

Teachers use their talk to scaffold students' ideas, often taking control or guiding them significantly for a variety of reasons (Berland & Hammer, 2012; Bleicher et al., 2003; Scott, 1998). For example, Hofmann and Mercer (2016) found that teachers are often concerned that if they do not provide enough support to their students, they will get "stuck" on a problem and waste time. However, despite their teacher's fears, in order to authentically practice engineering, students need to have control of their ideas and have opportunities for their ideas to both succeed and fail. Additionally, student thinking and behavior is strongly affected by what their teachers say (Dong et al., 2015; Pimentel & McNeill, 2013; Webb et al., 2009). Therefore, it is important that teachers model effective and authentic engineering in how they talk to their students. Teachers must perform the challenging balancing act between giving too much guidance as to overly constrain students' ideas and giving too little guidance that would lack the support students need to practice complex design processes.

This study uses the theoretical framework described here to frame the analysis of the data. This framework allowed for an analysis across both different levels of support from the teacher and a definition of engineering design to use in identifying what kinds of support are most applicable when students are engaged in engineering design projects.

3.3 Methods

3.3.1 Approach

This study employed a naturalistic inquiry approach (Lincoln & Guba, 1985). Naturalistic inquiry aims to work with participants to understand them without disturbing their natural actions. Therefore, this approach allowed an in-depth look at the ways in which teachers actually used their talk in small team interactions with their students without unduly influencing their actions. The process of naturalistic inquiry first involves making initial contact with the participants and gaining their trust. To plan design for the inquiry, the researcher must develop a "broad plan" for the study, including framing the bounds of the study, data collection and analysis, while anticipating contingencies that might arise. Naturalistic inquiry has 14 characteristics, which were used in this study. The research was conducted in the *natural setting* to demonstrate practices of teacher talk as they actually played out in the classroom. The *human instruments* were the researchers examining and analyzing the data. Examining all of the actions of the participants *used tacit knowledge*. The study used *qualitative methods, grounded theory* (as defined by Lincoln and Guba (1985), which simply refers to starting with no a priori theory for what will be seen within the data encountered), *inductive data analysis,* and *emergent design* by first using an open-coding process using all the data and refining this coding scheme through an iterative process. *Purposeful sampling* with *focus-determined boundaries* was used to choose the classrooms, by choosing classrooms from different grade levels and subject areas to encompass the range of different interactions and choosing effective teachers in each of these grade levels. To report the data, the researchers worked to *negotiate outcomes* and *use a case study reporting mode*, *idiographic interpretation*, and *tentative application* by providing rich descriptions of the data and themes in the context of the specific study to provide insights without making generalizations beyond the realm of the study. *Special criteria for trustworthiness* were developed, described in the data analysis procedures section, because "conventional trustworthiness criteria" are "inconsistent with the axioms and procedures of naturalistic inquiry" (Lincoln & Guba, 1985, p. 42)

3.3.2 Context and Participants

This study focused on six teachers during their implementation of engineering design-based STEM integration units in their classes, Ms. Lane, Ms. Allen, Mr. Parker, Ms. Stone, Mr. Reed, and Mr. Smith, all pseudonyms. The teachers all taught in the same rural school district, two teachers each from sixth, seventh, and eighth grades. The seventh and eighth grade teachers taught science at a junior/senior high school and comprised all of the science teachers for the junior high students. The sixth-grade teachers taught at different K-6 feeder schools to the junior/senior high school. They were the self-contained classroom teachers for their class and were responsible for teaching science to all two or three sixth grade classes while other teachers were responsible for other specializations. For both sixth-grade teachers, the data used in this study is from their primary class of students. The demographic information for the school district is displayed in Table 3-1. These demographics were taken from the National Center for Education Statistics (NCES) and are representative of the classes included in this study.

Table 3-1. *Demographic information for the school district*

Demographic	Percentage
Race/Ethnicity	
White	94
Black	1
Hispanic or Latino (of any race)	4
Two or more races	1
Students with a disability	11
Language other than English spoken at home	5
Free or reduced-price lunch eligible	49

Each teacher implemented a STEM integration curriculum unit developed by the EngrTEAMS project, funded by an NSF grant. Prior to the implementation of the units in their classrooms, the teachers participated in a week-long summer professional development program conducted by the authors and other researchers. During this professional development program, the teachers worked through the entirety of the curriculum unit that they were going to implement. They engaged in the activities and completed the engineering design project in small groups with the other teachers from their grade level. They also met as a larger group across grade levels to learn about STEM integration and engineering more generally and to practice using rubrics for assessment.

The 6th grade classes implemented the unit called Laser Security System, 7th grade implemented GotGMOs, and 8th grade implemented Ecuadorian Fishermen. The context for each unit is described in Figure 3-1. All the units had similar structures but focused on a different design challenge and different science and mathematics content. Each unit began with students receiving a letter from a fictional client with a problem. Then, the students engaged in problem scoping using a series of prompts that were the same for all units, including identifying the problem, why it was important to solve, and what they needed to learn to solve the problem. The students then spent several class periods learning the science and mathematics content they needed to solve the engineering problem through laboratory experiments and other student-centered activities. The students next engaged in planning, implementing, testing, evaluating and redesigning their solution. Finally, the students communicated their solution either through writing a letter back to their client or giving a presentation aimed at their client. Throughout the unit, the students maintained engineering notebooks where they recorded their ideas, responses to prompts for each stage of the design process (which were the same for all units), and data and information from the science and mathematics focused lessons. In general, all the teachers followed the curriculum closely with a few exceptions. Ms. Allen did not have her students communicate their results back to their client. Mr. Reed did not separate the stages of planning and implementing, rather the students engaged in these processes in a more fluid manner than in the other classes.

Although the units had similar structures, the products that the students produced were different in each unit. In Ecuadorian Fishermen, the students developed a physical prototype using a variety of materials and tested their prototypes in a physical solar oven. In GotGMOs, the students developed a process to prevent and test for contamination of non-GMO crops by neighboring GMO crops. Their finished product was a process plan, rather than a physical prototype. In Laser Security System, the students developed a physical prototype by planning their system on a large sheet of graph paper and arranging mirrors, lenses, and their artifacts on top of their plan. Therefore, they were able to physically test it with a laser pointer, but planning their solution took much more time than building their prototype.

Unit Name	Science Content Focus/Grade Level of implementation	Description of the problem for each unit
Laser Security System	Light and Waves 6th grade	Laser Secure, Inc., designs security systems to protect valuable assets. The company is seeking help from students to design a laser security system to protect the artifacts in a traveling museum exhibit. In the unit, students investigate properties of light, including reflection, refraction, absorption, and transmission. Their solutions must protect the artifacts by having an intruder cross the light from the laser pointer at least three times between entering the door and encountering the artifact using mirrors, lenses, and a laser pointer as their materials.
Ecuadorian Fishermen	Heat transfer 7th grade	A team that works with small businesses in Ecuador has discovered that some of the Ecuadorian fishermen need help. Once the fishermen return to the fish markets, they need a small cooker container to cook the fish so they can be sold. Students design this cooker container and build a prototype using simple materials they investigate throughout the unit. Students learn about the science of heat transfer, including conduction, convection, and radiation. They analyze data by creating temperature vs. time graphs and comparing different line graphs qualitatively.
GotGMOs	Genetics 8th grade	The University of Minnesota's Agricultural Department needs to determine if a new barrier effectively reduces cross-contamination of non-GMO corn fields from genetically modified organism (GMO) corn fields. Students learn about GMOs and mathematical and scientific concepts related to genetics and heredity, and use what they know to develop a strategy to test for cross-contamination once the newly proposed barrier is installed. They evaluate the designs to assess how they meet the specifications of the client.

Figure 3-1. Descriptions of EngrTEAMS curriculum units.

The length of the units in each class varied from 3-5 weeks. The number of class periods for each class is displayed in Table 3-3. All the classes had class periods of about 45 minutes in length (with some exceptions for alternative scheduling days, e.g., snow days), except Ms. Lane's class, which had 30-minute class periods. This study focused on the times when the students were working in their teams during the design portions of the units, including problem and background at the beginning of each unit and solution generation and refinement towards the end of the units.

Each teacher chose two teams of students in their class to be the target teams. The teams were chosen by the teachers. Some of the teachers chose the teams based on their location in the classroom (e.g., they were easy to see on the camera) and some chose the teams because the team contained students who they thought would talk a lot and therefore have a lot of data. Information for each team is displayed in Table 3-2**Error! Reference source not found.**.

Table 3-2. *Team information*

Teacher	Team Number	Students	Pseudonyms used
Ms. Lane (6th grade)	1	2 girls, 1 boy	Lily, Lexi, Logan
	2	3 boys	Lewis, Lucas, Liam
Ms. Allen (6th grade)	1	3 boys	Alex, Aaron, Adam
	2	3 girls	Amelia, Abby, Anna
Mr. Parker (7th grade)	1	2 girls, 2 boys	Paula, Penny, Peter, Pablo
	2	1 girl, 2 boys	Phoebe, Pat, Paul
Ms. Stone (7th grade)	1	2 girls, 2 boys	Sophie, Sarah, Simon, Steve
	2	2 girls, 2 boys	Sienna, Sally, Sam, Seth
Mr. Reed (8th grade)	1	2 girls, 2 boys	Ruth, Rebecca, Rick, Roy
	2	2 girls, 2 boys	Rachel, Rose, Robert, Rhett
Mr. Smith (8th grade)	1	2 girls, 2 boys	Sylvia, Sarina, Scott, Sean
	2	3 girls, 1 boy	Sue, Stella, Sadie, Sylester

3.3.3 Data collection

Data were collected throughout the entirety of the implementation of the STEM integration units and consisted of video recordings of the entire class, videos recordings focused on each of the two focus teams, field notes, student work, and pictures. For this study, the analysis focused on the videos of each team of students and the primary data were collected from video recordings of teams with the whole class video used as a secondary source to observe the teachers' movements through the classroom and pick up audio that was difficult to hear on the team videos. The videos were recorded with an iPad camera placed at the worktable of each focus team. These videos were recorded with a wide-angle lens that focused on a view of the table that the students were working on. Additionally, the teacher's voice was recorded with a transmitter attached to the teacher on the whole class video. The data collection focused on the parts of the units when students were actively engaged in the engineering design project, including the first lesson when students were problem scoping and later lessons when students were working on planning, trying, testing, redesigning, and communicating their results back to their client. Within this subset of lessons, the data collection focused on the periods when students are actively working with their teams and not the periods when they were individually working or engaged in whole class discussions or lecture.

To organize the data, all interactions between teachers and their students while the students were engaged in the engineering design aspects of the unit were transcribed. Table 3-3 displays a summary of the data. The vast majority of the teachers' talk was clear to understand; of the 403 interactions included, teacher talk in six interactions were partially or completely inaudible. In addition to the transcriptions of the dialogue between the teacher and students, notes were also kept about the students' actions immediately before and after the interaction, where they were in the engineering design process, and any other general notes about the interaction.

Table 3-3. *Summary of teacher team interactions*

Teacher	Team #	Number of interactions	Average length of interactions (min:sec)	Total number of class periods included in analysis
Ms. Lane	1	31	0:24	9
	2	39	0:25	
Ms. Allen	1	35	0:36	9
	2	32	0:38	
Mr. Parker	1	40	0:28	11
	2	40	0:16	
Ms. Stone	1	21	0:26	9
	2	43	0:35	
Mr. Reed	1	28	1:08	8
	2	33	0:58	
Mr. Smith	1	31	0:38	8
	2	30	0:43	
Total		403	0:35	

Although each unit had similar structures, each teacher had different styles of teaching that played out in different ways in their interactions with their students. Each teacher talked to their students differently and in different amounts. Table 3-4 displays the total number of words spoken by each teacher over the course of the unit.

Table 3-4. *Total number of words spoken by each teacher during all teacher-team interactions*

Teacher	Total words spoken
Ms. Lane	1510
Ms. Allen	3293
Mr. Parker	2693
Ms. Stone	3380
Mr. Reed	5679
Mr. Smith	3164

Both 6th grade teachers were at K-6 schools and were the primary classroom teachers for each of the classes that were examined in the study. Therefore, the teachers knew their students from multiple contexts, not just science class. Although Ms. Lane's (6th grade) schedule only allowed for 30 minutes of science per day, she used this time very efficiently and expected her students to do the same. For example, she expected her students to be ready at the beginning of the session with their notebooks out and held her students accountable for promptness. She moved around the classroom quickly, often checking in with her students for short periods of time and only staying for longer discussions in rare instances. This pattern is shown in Table 3-3, which shows that Ms. Lane had among the shortest average length of her interactions with her students compared to the other teachers. Ms. Allen (6th grade) clearly showed that she cared for her students, often calling them endearments such as "sweetheart" and checking that they were feeling well and getting along. Many of her interactions with teams of students had high levels of student talk compared to the other teachers, as shown in the examples presented later in this paper. Mr. Parker (7th grade) was the only teacher in whose classroom the students did not always sit in tables with their teams. In Mr. Parker's class, the students sat at tables with one other student and turned around to put their tables together for team work time. When students were working in teams, Mr. Parker was diligent about going to each team in turn, and he often had similar interactions with each team. Table 3-3 shows that Mr. Parker had the exact same number of interactions with both teams and was the only teacher to do that. Ms. Stone (7th grade) rarely initiated interactions with students. After giving instructions about the content and activities to the whole class, she let students work, only interrupting them when absolutely necessary, such as when she overheard a major misconception or when students asked a question. This pattern resulted in a much different number of interactions between the two teams in her class, as shown in Table 3-3, because team 2 asked a lot more questions than team 1. Mr. Reed (8th grade), on the other hand, had very little whole class time.

The students spent the majority of their time working with their teams with Mr. Reed giving instructions directly to teams as needed, rather than giving instructions to the whole class, resulting in much longer interactions than the other teachers, shown in Table 3-3. Mr. Smith (8^{th} grade) had a colloquial attitude with his students, often joking around with them. He spent much more time than the other teachers talking with students about things not directly related to their design project.

3.3.4 Data Analysis

Data analysis consisted of several cycles of coding (Saldaña, 2016). First, to start the data analysis, an open-coding process was used in conjunction with the transcribing process. Data were transcribed by the lead researcher in a spreadsheet with separate columns for each of the recorded aspects of the data, including the time stamp, classroom identifier, actual dialogue, etc. for organization. As the data were transcribed and the interactions were observed in the video recordings, notes were kept about potential codes. After transcription of the interactions for three of the six teachers, a preliminary coding framework was developed, including naming codes and writing descriptions of each code. During the transcription process for the next two teachers, each of the interactions was compared with the preliminary coding framework to ensure that the content of each interaction was represented in the coding framework. When there were examples that did not fit into the coding framework, the framework was adapted. Next, the lead researcher worked with an additional researcher to code several sections of the transcripts together to refine the definitions of each code, the boundaries of each code, and to ensure that all content of the interactions was represented in the codes. These steps resulted in several more changes to the coding framework. As the final teacher's data were transcribed, the interactions were again compared with the coding framework to ensure that all the content of the interactions was represented. Figure 3-2**Error! Reference source not found.** displays the final coding framework. Examples of each of the codes are presented in the results section.

Code group		Specific code	Description
General Classroom management		Check on progress	Teacher checks on students' progress, timing to complete tasks, checks that the students are doing what they are supposed to be doing, or tells them to get back on task.
		Clarify instructions	Teacher clarifies what the students should be working on or addresses questions about instructions students were given.
		Give next task	Teacher gives students their next task or reminds them of task.
		Manage grades	Teacher talks about anything related to grading.
		Manage materials	Teacher distributes materials, manages safety of materials, or anything else related to material use.
Teamwork		Encourage teamwork	Teacher encourages students to work with their teammates and/or gives them specific strategies to use to work with their teammates more effectively.
		Moderate disagreement	Teacher steps in to moderate or help resolve a disagreement between team members. Disagreement could be related to competing design ideas or anything else the students are doing.
Communication		Ask for justification	Teacher asks students to justify their ideas, improve their justifications, or explains why it is important to justify ideas.
		Direct communication advice	Teacher directly tells students how to communicate their ideas, such as giving them a sentence starter or restating something they said more clearly.
Design	Problem scoping	Encourage problem scoping	Teacher encourages problem scoping without giving direct ideas, including asking students to think broadly about the problem and/or posing questions to encourage students' thinking about the problem.
		Direct help	Teacher directly helps students break down the problem.
	Design Ideas	Prompts to elicit student ideas	Teacher asks about students' ideas or restates students' ideas without suggesting changes so they can actively listen to students' ideas.
		Follow-up	Teacher asks follow-up questions for students' ideas or points to follow-up ideas to consider without giving ideas directly.
		Critique	Teacher critiques specific aspects of students' ideas or the students' design, but without giving suggestions for improvement. Critique can be either positive or negative.
		Directly suggest ideas	Teacher directly suggests ideas to the students.
	Overall design process		Teacher talks about the overall design process, reminds students of other phases of the design process, explains why they need to do things a certain way to follow the design process, or holds students accountable for completing all the parts of the design process.

Figure 3-2. Descriptions of each code

Figure 3-2 continued

Other Engineering	Build engineering identity	Teacher says anything related to building an identity as an engineer.
	Reference engineering notebooks	Teacher tells students to reference their notebook, such as checking data in their notebook from earlier in the unit.
	Clarify engineering words	Teacher clarifies or redefines engineering words for students, such as client, end-users, etc. Criteria and constraints fit here if the teacher is defining them generally, not the criteria and constraints of the particular problem they are working on.
	Clarify criteria/constraints	Teacher clarifies the criteria and/or constraints of the problem or teacher brings up the criteria and/or constraints with the students.
	Learn from Failure	Teacher talks about learning from failure of design and/or how failure of design does not mean the person failed.
	Prompt student decisions	Teacher reminds students that they have control of their design and ideas or explicitly tells students that they need to make the decision.
	Use Tools	Teacher suggests or demonstrates how to use the tools the students are using for the design.
	Discuss Trade-offs	Teacher discusses the tradeoffs of students' design or poses questions to get the students to think about the tradeoffs of their design, with or without using the word trade-offs.
Math/Science	Prompt science and/or mathematics content	Teacher reminds students about science and/or mathematics content from the unit without telling the students any ideas directly.
	Direct support about science or mathematics content	Teacher clarifies science or mathematics concepts, clarifies misconceptions about the science and mathematics content from the unit, or talks to students to further their understanding of science or mathematics concepts.
Other things	Marginally related conversation	Teacher talks about something that is marginally related to the unit, such as when student asks about a science topic that they thought of because of the unit.
	Unrelated conversation	Teacher and students have a conversation not related to the unit, such as when the teacher admires a student's Rubik's cube skills
	Check wellbeing	Teacher checks on students' well-being, such as if they have eaten enough or if they are sick.
	Relationships outside classroom	Teacher asks about students' prior knowledge or what they have done in other classes or outside of school or teacher relates what they are doing to something outside the classroom.
	Teacher as student	Teacher indicates that they need to learn more or that they want to learn from the students.

To apply the coding framework to the data, each transcript was imported into NVivo 12, and all of the teacher's talk for all of the interactions during the entirely of each of the six implementations of the engineering design-based units were coded. Only teacher talk was coded, not student talk. Only coding the teacher talk allowed for a more direct analysis of just the teacher's talk and better references to compare across teachers. Furthermore, the students' talk and responses to the teacher presents in and of itself interesting insights that warrant its own study to focus on. Although the lead researcher did the majority of the coding independently, some of the data was also coded by another researcher to reach consistency of coding. NVivo 12 was used to isolate examples of each code which were chosen to represent each code later in the results section. The matrix functions in NVivo 12 were also used to quantify the number of words of each code and compare proximities of each code to look for patterns across codes.

3.3.5 Trustworthiness

The study was designed to ensure the trustworthiness of the data analysis throughout the process. The activities of prolonged engagement, persistent observation, and triangulation were employed by using data from six different classes, and the researchers engaged with the data over an extended period of time to transcribe and play with the data. The strategy of peer debriefing was used by discussing the work with others outside the data analysis process and asking them to look at specific areas of the data to confirm the patterns. The findings and coding scheme were refined until "it account[ed] for all known cases without exception" (Lincoln & Guba, 1985, p. 309). Referential adequacy was ensured by organizing the data and analysis in a logical way that will be accessible for future analysis and critique.

3.4 Results

The six teachers analyzed in this study talked with teams of students about a variety of topics. This section presents examples of each of the codes (descriptions of the codes are in Figure 3-2). Throughout this section, most examples include talk from multiple codes to provide context for the conversation. Therefore, in order to distinguish the pieces of each example that illustrate each code, words coded as the relevant code are bolded. During the coding process, if teacher talk fell within multiple codes, it was coded multiple times. Therefore, some of the examples were coded in other codes along with the ones they are used to illustrate. All names used are pseudonyms.

The codes were divided into seven larger groups, as described in Figure 3-2. The total number of words spoken by all the teachers for each code group during each phase of the design process is shown in Figure 3-3.

Phase of Design Process	Total Number of Words	Code Group						
		Classroom management	Teamwork	Communication	Design	Other Engineering	Science and mathematics	Other
Problem and background	2002	648	68	44	934	289	15	4
Plan	12650	3066	256	854	4747	1185	2108	434
Implement	1188	647	22	120	264	34	49	52
Test and Eval	3417	1967	31	25	892	158	0	344
Redesign	2627	673	37	65	1375	195	236	79
Communicate to Client	3534	1589	305	88	739	483	0	518
Total number of words		8590	719	1196	8951	2344	2408	1431

Figure 3-3. Summary of total words spoken by all teachers for each code group.

Figure 3-3 displays that most of the teachers' talk fell into the design code group followed by general classroom management. Additionally, the teachers talked to their students the most during planning. It is important to note that each of the teachers spent different amounts of time on different phases of the design process and each row in Figure 3-3 does not represent equal amounts of class time or equal numbers of interactions. The number of words displayed in Figure 3-3 are only the teacher talk, not student talk. Therefore, the number of words does not correspond to the length of interaction; longer interactions could have occurred with few teacher words if students did most of the talking. Each of the teachers had different styles of interaction and talked to their students for different amounts, so the teachers are not equally represented in the total words. **Error! Reference source not found.** displays the total number of words spoken by each teacher.

3.4.1 Design.

The largest number of words of teachers talk was coded into the design code group, as shown in Figure 3-3. This code group was broken down into three sub-code groups: *problem scoping,* which included *encourage problem scoping* and *direct problem scoping help*; *design ideas,* which included *prompt students to share ideas, follow-up, critique, and directing suggest ideas*; and *overall design process.*

Figure 3-4 displays the total number of words in each code for all the teachers. Figure 3-5 displays how the codes were distributed for each teacher.

Phase of Design Process	Design Total	Problem Scoping		Design Ideas				Overall Design process
		Encourage problem scoping	Direct support	Prompts to elicit student ideas	Follow-up	Critique	Directly suggest ideas	
Problem and background	934	117	134	336	240	154	0	0
Plan	4747	171	81	1265	1421	872	903	62
Implement	264	0	0	70	42	39	113	0
Test and eval	892	16	0	420	343	146	12	0
Redesign	1375	0	71	446	251	216	358	33
Communicate to client	739	0	0	157	18	93	445	26
Total number of words	8951	304	286	2663	2315	1520	1831	121
Number of interactions that included each code		9	7	111	48	49	42	6

Figure 3-4. Summary of number of words coded for each design code for all teachers.

Phase of design process	Teacher	Problem scoping		Design Ideas				Overall design process
		Encourage problem scoping	Direct support	Prompts to elicit student ideas	Follow-up	Critique	Directly suggest ideas	
Problem and background	Ms. Allen			10	11			
	Ms. Lane		42					
	Mr. Reed	30			6			
	Mr. Parker	65	89	275	178	154		
	Mr. Smith	22	3					
	Ms. Stone			51	45			
Plan	Ms. Allen			248	198	206		42
	Ms. Lane			148	56	9	358	20
	Mr. Reed	171	81	516	873	388		
	Mr. Parker			107		14	259	
	Mr. Smith			129	182	249	89	
	Ms. Stone			117	112	6	197	
Implement	Ms. Allen			32	23	5		
	Ms. Lane							
	Mr. Reed							
	Mr. Parker			31			82	
	Mr. Smith			7	19	34		
	Ms. Stone						31	
Test and evaluate	Ms. Allen			105	97	43	12	
	Ms. Lane			90	42	74		
	Mr. Reed			71	59	9		
	Mr. Parker			42	61	18		
	Mr. Smith	16		81	84	2		
	Ms. Stone							
Redesign	Ms. Allen			142	34	125	92	
	Ms. Lane							
	Mr. Reed							
	Mr. Parker			163	110	6	101	
	Mr. Smith		71	16	96		3	33
	Ms. Stone			125	11	85	162	
Communicate to client	Ms. Allen							
	Ms. Lane				18	7	16	
	Mr. Reed			15		46	389	26
	Mr. Parker			44				
	Mr. Smith			79		40	40	
	Ms. Stone			19				

Figure 3-5. Number of words coded within the design code group for each teacher.

Problem scoping.

The majority of problem scoping conversations occurred during the early stages of the design process, namely the problem and background and planning lessons, as shown in

Figure 3-4**Error! Reference source not found.**. The examples of problem scoping fell into two levels, *encourage problem scoping* and *direct support.*

Only three teachers used their talk to *encourage problem scoping*, as shown in Figure 3-5. Their talk in this code served to prompt students to think about what they need to do to understand the problem. All three of these teachers had examples during the problem and background lesson, such as when Mr. Parker said:

> So spend the most time seeing if you can come up with a refined team response for what is the problem that we have been asked to solve and why is it important to the client that we come up with a solution. OK?

As Figure 3-5 displays, Mr. Reed was the only teacher to *encourage problem scoping* during the planning stages, with examples such as when Mr. Reed said, "So if we go back, what was the problem that James Randolf [the fictitious client] wanted you to be able to solve?" and "What are some of your constraints?" He often used these examples while he was introducing the next steps and activities for the students to work on in their teams, reminding them of the problem and reason for their work before assigning the next step in the process. Mr. Smith was the only teacher to *encourage problem scoping* during test and evaluate with two examples, "think about your criteria" and "one of their, one of the criteria was to be reliable, right?" These examples demonstrate how the teachers worked to remind the students that they needed to problem scope but did not give any direct answers about what the problem was.

On the other hand, examples of *direct problem scoping help* included much more direct talk from the teachers. *Direct problem scoping help* was used rarely by all the teachers, as shown in

Figure 3-4 and Figure 3-5. For example, when Mr. Parker's students were working on problem scoping and were confused about the boundaries of the problem, they had the following conversation:

Mr. Parker: So, are you asking about the solar oven itself or the container?

Paula: I was thinking more like a mixture of both, the container and the microwave.

Mr. Parker: **So, I think if the solar oven is portable or not, I don't know if that's relevant. But I think what's more relevant is the container that's going into the solar oven. So that's what we've been asked to design, is the container itself that's going into the solar oven. Not necessarily the solar oven, or how it's going to work, I don't know if that's going to be relevant.**

In this example, the students appeared to misunderstand if they were designing the solar oven or the cooker container to use in the oven, so Mr. Parker directly helped them to understand the problem.

Although these examples demonstrate different levels of problem scoping support for different levels of understanding that the students had, they do not represent a wide breath of problem scoping conversations. Additionally, examples of problem scoping were rare in later stages of the design process, and when they did occur, were short and without follow-up. This pattern indicates that the teachers engaged in few conversations with their students about problem scoping and the conversations they did have were short or superficial.

Design Ideas.

The teachers spent a large amount of their talk discussing design ideas with their students, as shown in Figure 3-3. These conversations fell into four different levels of support from the teacher: *prompts to elicit student ideas, follow-up, critique,* and *directly suggest ideas.*

Prompts to elicit student ideas.

All of the teachers spent a significant portion of their talk on *prompts to elicit student ideas* during multiple stages of the design process, as shown in

Figure 3-4 and Figure 3-5. During these interactions, students were often the ones who did most of the talking. Therefore, the number of words displayed in

Figure 3-4 and Figure 3-5, which display only teacher talk, underestimates the amount of time spent on this code with respect to the other codes. For example, Mr. Smith had the following conversation with a team of students as they were working on their plan:

Mr. Smith: **OK, so what's your solution?**

Sylvia: Um, [looking at notebook] we're going to go to the local tree farm and buy enough pine trees to outline the fields, full grown trees, and then we're going to buy dirt and make high mounds for the parts where like the wind blows towards our fields [gestures with hand to mimic wind]. Like where the, we're going to find out the percentages of like wind and all that.

Scott: And then build grass over that so we don't lose dirt.

Sylvia: So yeah, so the dirt won't fly away.

Mr. Smith: OK, so that's the first part of your solution.

In Ms. Allen's class, a team had the following conversation as they were testing their design to confirm that the laser light hits the thief three times before it reaches the artifact in the museum:

Ms. Allen: '**Kay, explain it to me as he** [the thief] **goes through there, Alex.**

Alex: So it comes through here, as you see the door [moves thief model through prototype system]. OK, get that, you got that right? So he's right here.

Ms. Allen: **That's the entrance.**

Alex: OK, so he's going through. Well, let me see. He walks through here and then it refracts.

Student: So even if

Student: Over here, over here, over here.

Student: OK, so let's go this way. So he hits at one

Student: One, but then it goes right here again. So two.

Student: After it refracts, after it reflects off this. And then he passes the laser right here.

Student: He passes right here. Three.

Mr. Parker had the following conversation with his students as they were working on constructing their prototype:

Mr. Parker: Now, this is looking interesting. **May I ask what's going to happen? Is this the bottom or the top?**

Phoebe: That's the bottom.

Mr. Parker: That's the bottom. **So it's like triangular in shape now?**

Pat: Yeah

Mr. Parker: **OK, and those are the sides that are going to fold up?**

Pat: And then we're using aluminum foil.

In these examples, the teachers did not comment on the ideas, simply listened to the students' explanations and asked questions to support the students' explanations of their ideas. They allowed space for students to explain their ideas and added input as needed to keep them talking or to indicate that they were listening and understanding. These examples demonstrated opportunities for students to be owners of their ideas and have control of how they represented those ideas to their teacher.

Follow-up.

Teacher *follow-up* of design ideas included all instances where the teacher prompted students' further thinking about their ideas. Examples occurred throughout the design process, such as during planning in Ms. Allen's class:

Amelia: Since they're [the lenses] curved, they [the laser light lines] would go at an angle when they get off.

Ms. Allen: The lenses? You're thinking the lenses?

Abby: Yeah, that's what I'm talking about.

Amelia: They reflect though.

Ms. Allen: **Do they do both** [reflect and refract]?

Amelia: Yes

Ms. Allen: **OK. So would you have two then rays of light coming from a lens?** [Amelia nods] **OK, so that's something to consider too, right?**

When a team was working on their plan and explaining their design to the Ms. Stone, they had the following conversation:

Ms. Stone: **Why'd you pick the copper for the bottom?**

Sam: Because it absorbs the heat

Seth: It's more durable, that's why. Like to be able to support it.

Sienna: The aluminum won't take in heat.

Ms. Stone: **Do you think it will conduct any of the heat as well?**

Sam: I never thought of that.

Each of these examples prompted the students to think further about their design. In Ms. Allen's example, she explicitly told them "that's something to consider", and in Ms. Stone's example, the student vocalized they had "never thought of that," indicating that the students are realized that the teacher was pointing them in new directions and to new considerations for their design. This *follow-up* added a new perspective to their design without giving specific, direct ideas about what they should do, leaving the decision open to the students. Additionally, both of these examples demonstrate *follow-up* that integrated the science concepts from the unit with the design ideas.

Critique.

Although the amount of teacher talk that was coded as *critique* was less than the other design ideas codes (shown in

Figure 3-4), critiques were still important for expanding the students' ideas. All of the teachers *critiqued* their students' ideas during planning and most of them also critiqued ideas later in the design process as well (shown in Figure 3-5). Critiques included both positive and negative critiques on ideas. Throughout the units, short pieces of praise were common, such as when Ms. Lane said "it's looking good guys," Ms. Allen said "you're on fire. Nice job," and Ms. Stone said "Alright, looks good so far." These phrases helped to give validation to the students' work and ideas.

Short phrases of criticism of their design ideas were also common, such as when Mr. Reed said "Well, hey, that's going to be really expensive for my company," as well as longer, more specific critiques, such as when Ms. Allen said:

> Because if, just as I'm looking at, and I'm not trying to be critical, but I can tell that this is a smaller portion of paper showing than this is, so it's not exactly perpendicular with this. Does that make sense? So this isn't parallel. Right, so you can, you can adjust it if it really bothers you that much and draw your shape in this direction. That's up to you, how precise you want to be with that.

The teachers' critique served to points out areas in need of improvement, such as the cost in Mr. Reed's example or the lack of precision in Ms. Allen's example. Examples of critique validated students' ideas or directed them to areas of concern in their design.

Directly suggest ideas.

Sometimes the teachers used their talk to *directly suggest ideas* to teams about what their design idea should be. For example, during redesign Ms. Lane directly told her students to move one of their mirrors:

> Ms. Lane: Well, what was it [the laser light] aiming for originally? What's this? Mirror? [points to plan in notebook]
>
> Lily: Flat mirror.
>
> Ms. Lane: **Just move it up a little** [moves mirror about 3 inches], **just move it here, you know, 'cause it's not going to get in the way of, if you have this one** [other flat mirror] **here and that one there.**

In a similar example from Ms. Allen's class, the team had the following conversation:

> Alex: Adam was holding it [the laser pointer] in the right position.
>
> Aaron: At the perfect spot.

Ms. Allen: **Well, do it again. Where's your clay? Use your clay to hold it in the perfect spot.**

In these examples, unlike with the other design idea codes in which the teachers prompted students to think about their design themselves, the teachers directly told them how to fix their problem to make their system work. In another example, when a team in Ms. Stone's class was redesigning their cooker container, they had the following conversation:

Ms. Stone: **One thing, one thing to think about is like, have you ever been in a big room with tall ceilings?**

Seth: Yeah

Ms. Stone: **And versus a smaller room with lower ceilings, which one'll heat up faster?**

Seth & Sadie: The smaller one.

Seth: So we could…

Ms. Stone: **So think about that, with…**

Seth: Make it smaller

Ms. Stone: **Yeah. Yep**.

In this example, Ms. Stone was also directly suggesting ideas to the students, however, she did it through prompting questions that closely guided her students to her idea, rather than telling them directly.

Unlike talk that fell within the other codes in this group, when the teachers used their talk to *directly suggest ideas*, students were not able to think through the challenges of their design themselves. On the other hand, these prompts may have provided the hints that the students needed to have a more testable or successful design that may have strengthened their understanding of the concepts of the unit.

Across design idea codes.

The design idea codes were not usually isolated from each other. The teachers used a variety of different levels of support for design ideas, and the different levels of support often followed each other. This pattern is shown, for example, in Figure 3-5, which shows that during multiple phases of the design process, most of the teachers used almost all of the design ideas codes. These instances were often used in conjunction with each other. A common pattern was that teachers used *prompts to elicit student ideas* and then asked *follow-up* questions. For example, Mr. Reed had the following conversation with a team of students as they were discussing the possibility of creating an artificial barrier. Words coded as prompts to elicit student ideas are bolded and words coded as follow-up are underlined.

> Mr. Reed: [Reading off students' paper] "cost per acre," might be like an average cost, "based on pound needed," OK, I'm lost. **What do you mean by pound needed?**
>
> Robert: You can make an artificial, you can make an artificial barrier of chemical that would kill the GMO pollen.
>
> Mr. Reed: <u>Ooo, but won't that, alright, here I'll be the devil's advocate. Won't those chemicals wash away? What do we mean by an artificial barrier?</u>
>
> Robert: Like a barrier made of man-made chemicals [Students continue to explain their ideas and propose other ideas].

In this example, Mr. Reed started by listening to the students' ideas. When something came up that he did not understand or maybe did not think would work, he asked questions to prompt the students to explain their ideas more and think more deeply about their ideas. This practice allowed the teacher a chance to understand the students' ideas and also ask follow-up questions to prompt improvements and further thinking.

Although the pattern of *prompts to elicit student ideas* followed by *critique* was less common, it occurred several times. For example, when Ms. Allen's students were working on planning their laser security system, they had the following conversation (words coded as prompts to elicit student ideas are bolded and words coded as critique are underlined):

> Abby: So the laser's here, right next to this mirror. But before it gets to the mirror, it goes through a lens.
>
> Ms. Allen: **Which one?**
>
> Abby: Uhhh [shrugs]
>
> Amelia: Either one, they're like the same thing.
>
> Abby: Yeah.
>
> Ms. Allen: **You think?**
>
> Amelia: They're the same thing.
>
> Anna: The lens is bigger.

Abby: Concave lens. and then, so it makes it refract, like what we were looking at yesterday. And then it has two lasers come out.

Ms. Allen: **Right.**

Amelia: So they go through each other?

Abby: No. Because remember when we were having…that yesterday, there's a lot of them [laser light lines] everywhere.

Amelia: It's just going through the lens.

Ms. Allen: <u>OK, but here's, here's what I want to ask you about. So if it comes through this lens, concave or convex, whichever one you put there, and we know that the angle that it's going to enter is not going to be the same as it leaves. So, you've got the reflection and the refraction within that, reflection and the incidence but then that refraction angle is going to be way different. They're not going to travel in the same direction, are they? So it might be like way over here somewhere, depending on where it hits on that lens.</u>

Abby: Well then I could move this here and put it here.

Ms. Allen: <u>OK, just be prepared for that.</u>

In this example, the teacher started by listening to students' ideas and asked short questions about their ideas that kept them talking. Rather than correcting them, she first let them talk among themselves. Later, she started to critique their ideas and point to areas of their idea that she thought might cause trouble for their design.

Overall design process.

As shown in

Figure 3-4**Error! Reference source not found.Error! Reference source not found.**, there was very little talk in which the teachers talked about the overall design process. One of these examples was from Ms. Lane's class when students were drawing their plan on their large sheet of graph paper on which they later laid out their design for testing the students wanted to use pen. She said:

> I would do pencil, because you're going to have to redesign later if it doesn't work and you'll have to redo everything if you need to change one thing, you know. I would do pencil.

In this example, the teacher reminded the students that they would be working on a redesign, not giving them any option but that they would do a redesign, and that they should prepare for that, in this case by using pencil so that they could more easily make changes. By having this conversation, Ms. Lane set up her students to be prepared to make changes to their design, thus helping them apply the design process iteratively. Another example of bringing attention to the overall design process occurred in Mr. Smith's class while students were finishing up their redesign.

Sarina:	How would we do another redesign?
Mr. Smith:	**So, it's a tough question. How could you take it a step further? If time and energy were not something you needed to worry about, how could you take it even another step?**
Sarina:	Build a wall.
Scott:	[at the same time] Better barriers.
Mr. Smith:	But you know that's OK, it's like a tradeoff, right? Like your, your criteria can be expanded a little bit. So yeah, it's going to take more time, but you didn't give me a specific time limit, it's just going to take more time, it's going to take more money. You want it to be cost effective, but we didn't really give an exact number for that, so you know, you could expand in that direction. And you just have to say that you acknowledge that it's more expensive. You know what I mean? **I don't know, just take it a step further.**

In this example, the students took the initiative to consider that another redesign might be needed. Mr. Smith responded by reminding them that the number of redesigns is limited by the time and energy of the designers, which is an important trade-off for engineers to consider.

Both of these examples provide first steps to helping students understand the entire design process and how it effects their design. However, there were very few instances like these, and these few examples were limited to specific aspects of the design process, rather than a more holistic view.

3.4.2 Classroom Management.

After design ideas, the second most number of words of the teacher talk fell within the classroom management code group, as shown in Figure 3-3. This high amount of teachers talk is not surprising as the teachers were managing many students, materials, and time constraints. The codes that fell into the classroom management code group are *check on progress, clarify instructions, give next task, manage grades, manage materials,* and *manage time*.

Figure 3-6 displays the breakdown of each of these codes, based on number of words spoken by the teacher, within each phase of the design process across all the classrooms.

Phase of Design Process	Classroom management total	Check on progress	Clarify instructions	Give next task	Manage grades	Manage materials	Manage time
Problem and background	648	243	208	74	0	52	64
Plan	3066	323	1247	1010	208	335	74
Implement	647	144	139	9	0	378	0
Test and Eval	1967	205	414	1004	20	392	0
Redesign	673	183	56	30	0	387	17
Communicate to Client	1589	225	870	111	116	322	0
Total words	8590	1323	2934	2238	344	1866	155
Total number of interactions that contained each code		139	105	34	7	100	8

Figure 3-6. Summary of number of words coded within the classroom management code group for all teachers.

Many of the teachers' interactions with their students began with the teachers approaching a team to *check on progress*, allowing the teachers to assess where the students were and how the teacher could support them. As Figure 3-6 displays, these examples occurred throughout the unit. Typical examples included when Mr. Parker asked teams "How's it coming along over here?" and Ms. Allen asked, "How're you guys doing?" before allowing students to explain what they were working on or ask questions that had come up. The teachers often asked about a team's progress with open-ended questions that left room for students to say anything. Their responses provided the teachers with information about how the team was doing and gave the team time to ask questions or otherwise interact with the teacher as they needed. Sometimes these interactions were short and the teacher left the team after confirming that the team was on track, and other times they expanded and included more discussion, as shown in later examples.

The teachers also spent a significant amount of their talk to *clarify instructions*. These examples occurred throughout the design process and usually consisted of the teacher re-explaining what the students should be working on. For example, during planning Ms. Lane's student asked:

Lewis: Is it OK if I draw it straight on here [the graphic organizer]?

Ms. Lane: **Yeah, just a quick drawing.**

The code *give next task* encompassed any interactions in which the teacher gave students instructions for the next activities to the team, rather than to the whole class. These also occurred throughout the design process. These interactions varied across the classrooms, with some of the teachers giving the major instructions to the whole class and others spending less time on the whole class and only giving the teams instructions as they were needed. The other classroom management code that covered a significant amount of teacher talk was *manage materials*. In all the units, the teachers spent a significant amount of their talk to support organizing, handing out, managing the safety of, and cleaning up materials.

The large use of classroom management language points to the large amount of time and effect needed for the many different and varied requirements of the activities while students were working on complex problems. Additionally, it emphasized the large role that classroom management plays in teacher-team interactions.

3.4.3 Teamwork.

The interactions in this study were between teachers and teams of students; however, the teachers spent relatively little of their talk on teamwork-related conversations. The number of words coded in the teamwork group of codes, including the codes of *encourage teamwork* and *moderate disagreement,* is displayed in Figure 3-7.

Phase of Design Process	Teamwork Total	Encourage teamwork	Moderate disagreements

Problem and background	68	45	23
Plan	256	252	4
Implement	22	16	6
Test and Eval	31	28	3
Redesign	37	18	19
Communicate to Client	305	298	7
Total number of words	719	657	62
Total number of interactions that included each code		33	7

Figure 3-7. Summary of number of words coded within teamwork for all teachers.

The majority of the teachers' talk about teamwork was used to *encourage teamwork,* rather than *moderate disagreements* among team members. Much of this talk occurred during planning. In all the units, planning required students to take their individual ideas, share them with their teammates, and develop a team plan. For example, to help facilitate this process, Ms. Lane said to her students, "Can we combine them [each team members' idea from individual planning]? Maybe get a highlighter out and say we want to use this part of this one [student's plan] and this one [part] of this one [student's plan]." In this example, Ms. Lane encouraged her students to work together as a team to develop their team plan and gave them a specific strategy to help.

There was also a significant amount of talk devoted to *encourage teamwork* while students were working to communicate their design back to the client. For example, while the students were working on slides for their presentation to their client, one of the students was talking through what he had worked on. Mr. Reed overheard him and interrupted the following conversation:

Rick: [Reading instructions] "Describe improvements made from previous designs." I did that. "Explain why the design was chosen over the other designs." I did that.

Mr. Reed: **Can we put some we's in there?** […]

Ruth: We each did two slides.

Rick: Yeah, we each did two slides.

Mr. Reed: **OK. Sorry, there was a lot of I, I, I**.

In this example, Mr. Reed encouraged the students to work together and to give credit to the team involved in developing the design, not just an individual.

Although the teachers spent less time on talk that was coded as *moderate disagreements,* the examples played an important role in helping teams work together. For example, during Mr. Parker's class, the students were having a heated argument about the best way to fit a piece of transparency over the top of their cooker container. Mr. Parker noticed the argument, then approached the team, and directly suggested an idea that would solve their argument:

Mr. Parker: **Can you trim it to size?**

Pat: Yes, we can [very frustrated]. They finally cooperated. [Teammates start cutting transparency to size, Pat takes deep breath] I can breathe.

A similar example occurred in Ms. Allen's class when students were planning:

Ms. Allen: What did you say, Adam, there?

Aaron: Um, well, we're still kind of bickering

Ms. Allen: **Bickering?** [squats down to be at eye level with students] **Well, here listen.** In your design, you used a convex lens.

Aaron: mm-hmm [agreement]

Ms. Allen: 'Kay. How does light behave when it hits a convex lens?

Aaron: Um, it refracts and reflects

Ms. Allen: OK and did you show that in your design? Did you use that?

Aaron: I did.

Ms. Allen: So then, you could list that when the laser hits a convex lens it reflects and refracts, right? [Students write in their notebooks].

In these examples, both teachers handled the disagreements by directly suggesting an idea that would resolve the issue that was the center of the argument. They used their power as the teacher to back up this method and to help the team get back on track, rather than having a conversation about how they could work as a team to resolve their disagreements.

Overall, the teachers minimally intervened in teamwork. Although there were several examples of teachers supporting teamwork, especially during planning and communicating, they used very little of their talk to support teamwork, instead letting students work together as they chose.

3.4.4 Communication.

The teachers used their talk to support communication throughout the design process, as shown in Figure 3-8. The codes for communication comprised *ask for justification* and *direct communication advice*. The majority of the examples fell within the planning phase, in part because of an activity that all the units shared that required students to complete a graphic organizer to explain their design ideas and justify their ideas using evidence from the mathematics and science content that they had learned in the unit. This activity involved a high number of interactions with the teacher both because it was challenging and required a significant amount of time to complete.

Phase of Design Process	Communication Total	Ask for justification	Direct communication advice
Problem and background	44	44	0
Plan	854	652	202
Implement	120	52	68
Test and Eval	25	20	5
Redesign	65	0	65
Communicate to Client	88	40	48
Total number of words	1196	808	388
Number of interactions that included each code		19	17

Figure 3-8. Summary of number of words coded within communication for all teachers.

Ask for justification included all examples in which teachers encouraged their students to justify their ideas, without explicitly telling them what to say or how to say it. For example, during planning, when the students were working on explaining why they chose their solution, they said it was the best. Mr. Reed responded with:

Mr. Reed: **If you were working for me and I was the client, I don't know what you mean by best, what do you mean by best? Gives the best results?**

Rhett: It gives the better results.

Mr. Reed: **Why? How do you know?**

Robert: Cause it has…

Rhett: It [genetic testing] would be better than just looking at it.

Mr. Reed: **How do you know?**

In a similar example, Mr. Parker had the following conversation:

Penny: Would the transparent tissue be good for the top?

Mr. Parker: **So, can you justify why? Why would we use transparency on the top?**

In these examples, the teachers encouraged their students to justify their ideas and to elaborate on why they chose to do what they did. They did not give their students any direct answers or critique their justifications, instead simply asking them to further explain their ideas.

In contrast, sometimes the teachers gave *direct communication advice* that more specifically told the students how to communicate their ideas. Often, these examples included sentence starts or other specific communication advice. For example, Ms. Allen and her students had the following conversation while they were planning their idea:

Ms. Allen: Can you be specific? What did you choose, which one?

Abby: The…Anna's

Ms. Allen: So we choose Anna's plan because [pauses to wait for students to respond]. **You just liked it better? It did a better job?**

Amelia: Because… [long pause]

Ms. Allen: **It met more criteria?**

Abby: Yeah, because it reflects a lot of times. So it covers, like there's a lot of lasers going so it's hard to get through it.

Ms. Allen: **OK. Write that down, yeah.**

In this example, Ms. Allen gave more direct support than the previous examples by giving suggestions of why they might have chosen Sarah's plan and direct suggestions about how they could talk about their ideas. Many of the examples of *direct communication advice* were centered on making their plans and ideas clear for others to understand. For example, when Ms. Allen's students were planning their laser security system, she had the following conversation with a team:

Ms. Allen: Where's your laser going to start?

Amelia: It's going to start over here [gesturing towards the corner of the plan]

Ms. Allen: **This is pretty general, why don't you like indicate on your paper, so somebody who's looking at your plan can tell.**

These examples of how the teachers discussed communication with their students demonstrate that the teachers prompted their students to justify their ideas and to develop skills to be able to communicate their ideas and the reasons for their ideas to others. Based on the needs of their students at a particular point, the teachers had to make decisions about how much support to give their students to help them communicate their ideas while still maintaining their own voice.

3.4.5 Other Engineering

Outside of design, there were many other aspects of engineering that the teachers discussed with their students. However, none of these were discussed as much as design ideas. Figure 3-9 displays a summary of the number of words spoken about each of the codes by all the teachers. Figure 3-10 displays a summary of which teachers' talk fell into each code for each phase of the design process. This section will provide examples of each of the codes.

Phase of design process	Other Engr total	Build Engr Identity	Reference Engr Notebook	Clarify Engr Words	Clarify Criteria/ constraints	Learn from Failure	Prompt Student Decisions	Use Tools	Discuss Tradeoffs
Problem scoping	289	0	0	101	188	0	0	0	0
Plan	1265	43	293	107	321	0	148	87	266
Implement	34	0	26	0	8	0	0	0	0
Test and Eval	70	0	14	9	17	32	0	0	30
Redesign	195	0	9	25	46	0	28	76	11
Communicate to client	495	0	15	222	0	0	90	181	43
Total number of words	2348	43	357	464	580	32	266	344	350
Total number of interactions that used each code		2	18	14	20	1	17	11	9

Figure 3-9. Summary of number of words coded within the other engineering code group for all teachers.

Phase of design process	Teachers	Build Engr Identity	Reference Engr Notebook	Clarify Engr Words	Clarify Criteria/ constraints	Learn from Failure	Prompt Student Decisions	Use Tools	Discuss Trade-offs
Problem and background	Ms. Allen			17					
	Ms. Lane			29	47				
	Mr. Reed								
	Mr. Parker			30	94				
	Mr. Smith			25					
	Ms. Stone				47				
Plan	Ms. Allen		72	46	156		16	35	
	Ms. Lane		126	61	105		7	52	
	Mr. Reed	43	36				46		12
	Mr. Parker						32		
	Mr. Smith		46		60		42		254
	Ms. Stone		13				5		
Implement	Ms. Allen								
	Ms. Lane								
	Mr. Reed								
	Mr. Parker								
	Mr. Smith		26						
	Ms. Stone				8				
Test and evaluate	Ms. Allen								
	Ms. Lane				17				
	Mr. Reed		14	9					
	Mr. Parker								
	Mr. Smith					32	13		73
	Ms. Stone								
Redesign	Ms. Allen		9		21		21		
	Ms. Lane			25					
	Mr. Reed								
	Mr. Parker				25				
	Mr. Smith								11
	Ms. Stone						7	76	
Communicate to client	Ms. Allen								
	Ms. Lane								
	Mr. Reed		12	89			68	158	
	Mr. Parker								
	Mr. Smith		3	65			9	23	
	Ms. Stone			68					

Figure 3-10. Total number of words coded within the other engineering code group for each teacher.

Build engineering identity.

As shown in Figure 3-9, there were only two instances where a teacher used their talk to *build engineering identity*. Figure 3-10**Error! Reference source not found.** shows that these were both from only one teacher, Mr. Reed. Both instances were during planning. The first example was, "…So if you were to think, if you're the engineer, and you're going to come up with…" and in a second instance he said, "Justify it for me why, why are you picking this. It's just like if Rick's [other student in team] doing engineering, why'd he picking this piece of equipment to use?" These examples are very limited and short in the scope of the whole unit and only indirectly point to developing students' identities as engineer

Reference engineering notebooks.

Throughout the unit, both the students and teachers relied on their engineering notebooks to record their ideas and to refer back to them. Therefore, there were several examples of the teachers asking or telling their students to *reference engineering notebooks,* especially during planning as shown in Figure 3-9. All of the teachers, except Mr. Parker, made some *reference to engineering notebooks,* as shown in Figure 3-10. For example, during an interaction when she was helping her students better understand the materials they were working with, Ms. Stone said to a team:

Ms. Stone: Was plastic an insulator or a conductor?

Simon: It was a conductor…I'm not sure.

Sarah: I'm pretty sure it was an insulator.

Ms. Stone: **Check your data. Did you remember when we did the ice cube melt** [experiment]? [flips back in student's notebook and discusses results of experiment].

When Ms. Lane's students were struggling to understand how to precisely measure the angles on their plan, they said:

Lucas: How are we supposed to measure this [angle that the light will refract] if we don't know how it comes out of the lens?

Ms. Lane: **You do know how it comes out of the lens. Look at your data. Like if I have a convex lens,** [looks at data table in student's notebook] **Where's the convex lens** [data in the notebook]? [Pointing to data table in student's notebook] **If it goes in at 30 degrees, it's going to come out at 35 degrees. Use these measurements.**

In these examples, the teachers pointed the students back to their notebooks to support their ideas while they were working on their designs. By using talk in this code, they were holding their students accountable for their earlier work, pointing to connections across the different activities that the students were engaged in, and bringing out the importance of using data and evidence in engineering decisions.

Clarify engineering words.

There was new engineering vocabulary that the students learned that sometimes required the teachers to *clarify engineering words*. This code was most common during the problem and background, plan, and communication phases of the design process, as shown in Figure 3-9, and was used by all the teachers at some point in the unit, as shown in Figure 3-10. For example, a team in Ms. Lane's class had trouble understanding what the solution meant:

Liam: What does it mean by "what's the solution?" [a notebook prompt]?

Ms. Lane: **OK, that's the solution. You had an engineering problem, to create, to create a laser security system, and you created a solution** [points to plan], **a laser maze.**

Liam: Yeah.

Ms. Lane: **So this is your solution. How did you choose this solution? What did you do? Because look, which solution did your team choose [**points to notebook]? **Here's a solution** [points to one student's plan], **here's a solution** [points to different student's plan], **you know. Y'all had different solutions.**

Liam: Oh, we used like some of his, some of his [pointing to partners].

In Mr. Smith's class, a team had trouble understanding who the client was:

Sarina: For client, um, would it be the farmer with like the GMO crops? Or who would it be?

Mr. Smith: **So who, so you're making a test, right? You're being asked to make a test? Who's hiring you to make the test?**

Scott: James Randolf [the fictitious client].

Mr. Smith: **That's the client.**

Scott: I told you guys.

In both of these examples, the students asked about the use of a specific engineering word, solution or client. The teachers responded by asking questions to prompt the students to think about the meaning of the word, given what they already knew about the problem. These interactions gave the students support to understand the new vocabulary and to relate it to their engineering problem.

Clarify criteria and constraints.

The teachers were often the one to *clarify the criteria and constraints* of the engineering problem. This code occurred the most during the problem and background and plan phases of the design process, as shown in Figure 3-9. Each of the teachers except Mr. Reed used at least some of their talk to *clarify criteria and constraints,* as shown in Figure 3-10. For example, one of Ms. Stone's students asked:

Steve: So, we can't like stack the fish on top of each other, right?

Ms. Stone: **Nope, you're just going to have one fish.**

Ms. Allen reminded her students, "**OK, so yes, it** [the thief] **would need to cross** [the laser light] **three times. Right there you have two, you need three"** and Ms. Lane had the interaction:

Lucas: Can our light shine through the artifact?

Ms. Lane: **I don't think so, no. Unless your artifact has a lens on it.**

In these examples, the students relied on the teachers to know the criteria and constraints that were both directly given and implied. In these examples, the teacher is the one who has the final say about the boundaries of the criteria and constraints and who determines if the students have met the criteria and constraints.

Learn from Failure.

There was only one example that was coded as *learn from failure,* as shown in Figure 3-9. During their testing and evaluation, a student in Mr. Smith's class was disappointed by the performance of their design:

Sue: We only got 11 [on the evaluation rubric].

Mr. Smith: **You only got 11? You're being honest. You're self-evaluating. Your design, not yourself, not yourself, not yourself. You're evaluating your solution. Which is inherently a piece of you, but you know.**

In this example, the teacher started to turn the student's disappointment into a learning opportunity about failure and honest evaluation. He did not elaborate further on learning from failure. There were no other examples in any of the classes that related to learning from failure.

Prompt student decisions.

As shown in Figure 3-10**Error! Reference source not found.**, all the teachers had a least one instance of *prompt student decisions*. Instances of this code were most common when the students were planning their design and communicating their ideas to their client, as shown in Figure 3-9. The teachers often explicitly told their students that they needed to make decisions in their design and that they were responsible for the final decisions about their design. For example, when discussing developing a solution for use in their local area, Mr. Reed said, “Well you’re a [name] county girl. Figure it out. I’m not from [name] county.” As a team was finishing up their plan, Mr. Parker said:

> Once you’ve figured out how much of each stuff that you’re going to purchase, **I will let you guys completely decide on how much you think you will need to build that box the size that you said,** and then come up to the front and you’re ready to get your materials. So just figure out how many materials you’ll need.

In these examples, the teachers told their students that they need to make decisions about their design and let the students take responsibility for their ideas, providing explicit opportunities for their students to practice making decisions. They emphasized that there was not a right or wrong answer, but that the students had to figure out their answer, allowing students to take control of their ideas and practice the design process by getting opportunities to follow through with planning, trying, and testing their ideas and learning from their mistakes and successes.

Several times, examples of *prompt student decisions* were said immediately after the teachers *directly suggesting ideas.* For example, Mr. Smith had the following conversation with one of his teams of students as they were planning. In this example, words coded as directly suggesting ideas are bold and prompt student decisions are underlined.

> Mr. Smith: **Can you do anything that would prepare it for being tested genetically?**
>
> Sarina: Hold on, I have to write this down.
>
> Mr. Smith: What did you do in here [this unit]? Did you do anything with DNA?
>
> Scott: The strawberries [DNA extraction lab].
>
> Mr. Smith: Yeah, you extracted DNA. **So technically, you could have him** [the farmer] **extract the DNA at home and send in a little bit of DNA for sampling and probably save a lot of money actually to send in the DNA itself instead of just the corn kernels.**
>
> Sylvia: Wait, so we’re going to tell him to extract…

Mr. Smith: <u>If you want to, that's up to you.</u>

Another example occurred in Mr. Parker's class, after students made a plan to put white felt on the bottom of their cooker container:

> Mr. Parker: Light, we learned, can shine through like the white felt, but if it's on the bottom, I don't think it's going to conduct heat very well up to the fish, **so you might use something that's a good conductor for the bottom of the container.** <u>But that's up to you guys to decide</u>.

These examples include a very specific suggestion and imply that the students should use that suggestion, immediately followed by a phase telling the students that their design is their decision.

Use Tools.

Sometimes, the students struggled to use the tools they needed for their design and the teachers used their talk to support their students to *use tools*. Examples of this code only occurred during planning, redesigning, and communicating to the client (Figure 3-9) and each teacher only used their talk in this code during one phase of the design process (Figure 3-10). For example, when students were working on their presentations to the client, Mr. Reed said to a team, "If everybody in that group has a computer out, it makes life much easier because you could share that document and each of you work on a slide." In this example, Mr. Reed gave a suggestion to the team about how to work more effectively with the tools they had.

In other examples, the teachers gave direct support to the students about how to use tools. When Ms. Lane's students struggled with using a protractor to measure the angles in their plan, she gave them direct support about how to use it to measure the angle in their plan, saying:

> OK, **So you want that** [angle]. [leans over table towards large sheet] **So what I would do is you're going to put this one** [moves lenses out of the way to place protractor**]. I would just draw like a little line** [uses protractor as straight edge to draw line] **and just say convex lens. And then from there I would draw another line perpendicular, I would go ahead and draw my dotted line.** Because in your notebooks [flips through one of the students' notebooks to find a page] you know how to measure everything from the line of normal. **So, going through with the protractor** [puts the protractor on the notebook page] **we measured all of this from our line of normal** [points out normal line and angle on diagram in notebook]. **This line here that goes up and this line here that** [Moves attention back to big sheet plan] **So now you're working on this, so you line up your protractor with your line of normal.** And you go.

In another example, Ms. Stone's students asked a specific question about the thermometers, which was an important tool in their heat transfer focused unit:

Seth: Shouldn't we all be using like the same thermometer so we all have the same accuracy?

Ms. Stone: **Since we're interested in change in temperature, you should use the same thermometer twice. So, it's OK if you use different thermometers because we're not interested in the beginning and ending temperature, we're interested in the change, so as long as you're using the same one both times.**

In these examples, the teachers gave support to the students about how to use the tools they needed for their designs. The students had used each of these tools, protractors or thermometers, earlier in the unit and were somewhat familiar with their use. However, in these examples, the teachers were supporting the tool use in a new context and in the application to their project.

Discuss Tradeoffs.

Mr. Smith was the only teacher to meaningfully *discuss tradeoffs* with his students, as shown in Figure 3-10, and there were nine examples throughout the units, as shown in Figure 3-10. For example, when students were working on deciding how often they needed to test the crops for cross-pollination as they were growing, they had the following conversation:

Sarina: Test it every day.

Mr. Smith: **Seems expensive.**

Scott: Test it once a week.

Mr. Smith: **It's an idea. And you can do it and there's benefits. It would be highly reliable probably because you'd know the moment** [snaps fingers] **you got contaminated, but the risk would be that it would cost a lot of money every day.**

And in another example in Mr. Smith's class as they were testing and evaluating:

Sue: Oh, but this is going to take forever then, cause it's going to take 10 years for a tree to grow.

Mr. Smith: **Well, but the, OK, so discuss how your solution would maybe take more time.**

Stella: But it would be worth it.

Mr. Smith: **But it would be worth it in the end. But you can buy trees that are pretty big, but not really like, you know, but that would be a lot**

more cost than buying small trees. So, it's a tradeoff, time versus cost.

In these examples, Mr. Smith talked to his students about both the good and bad aspects of their ideas. He pointed to the tradeoffs and explicitly told the students that they would have to balance these in their design.

This section provided examples of each of the codes in the other engineering code group: *build engineering identity, reference engineering notebooks, clarify engineering words, clarify criteria and constraints, learn from failure, prompt student decisions, use tools,* and *discuss tradeoffs.* These examples demonstrate interactions between the teachers and teams that pointed to many different aspects of engineering.

3.4.6 Science and mathematics

The examples of *science/mathematics* fell into two categories, *prompt science/mathematics content* and *direct support of mathematics or science.* Many of the examples that were coded as *science/mathematics* also fell into other codes. Therefore, many of the earlier examples given were coded as *science/mathematics* in addition to other codes they represented. The vast majority of examples of this code fell during the planning phase of the design process, as shown in

Figure 3-4.

The code *prompt science/mathematics content* included all talk in which the teacher did not give direct support of content. Often, these examples consisted of the teachers asking questions to remind students of the mathematics or science content of the unit while they were working on their design project. For example, as they were planning their system, Ms. Lane asked a team of students "How does the light go through the flat lens? […] Does it change at all? Does it have any refractions?" and when his students were working on deciding how to prevent pollen spread between fields, Mr. Smith asked his students "What is pollen? How does it transfer? Through what medium?" In addition to questions to prompt thinking about the science and mathematics concepts, the teachers also asked questions to prompt students to think about earlier learning experiences in the unit. For example, as they were deciding how many samples to test, Mr. Smith asked a team "So we did Punnett squares, right? And we talked about, and my example was if I flip a penny 10 times, how many times should it be heads and how many times should it be tails?" and when Ms. Stone's students were discussing which materials to use based on how heat would transfer through them, she asked, "Did it [the material] work well in our lab [points to data table] to increase temperature?" In these examples, the teachers were prompting students to think about science and mathematics content from the unit and reminding them of tasks they had done earlier in the unit that could help them in their design. These did not give specific information, but they did help point students to the relevant information and point to connections to their earlier learning experiences.

There were also examples in which the teachers were much more direct in their support, coded as *direct support of science/mathematics.* Most of these examples occurred after the students had struggled with concepts or aspects of their design. For example, when Ms. Lane's students were working on their plan, they were struggling to understand how the light would travel through a lens they had in their plan. Ms. Lane said:

Ms. Lane: **So if you put your concave lens here, if it's angle of incidence is, whatever it is** [gestures with hand to simulate laser light], **it's going to bounce off at the same angle of incidence, the same angle. Incidence** [gestures with hand moving towards lens] **and reflection [**gestures with hand moving away from lens] **are the same. So refraction** [gestures on the opposite side of the lens] **is the one that's** [points to data table in notebook] **about 5** [degrees] **off.**

Lily: So we need to know if that's clear coming over here [points to plan]?

Ms. Lane: Yeah, if that's how the angle is, you'd have to measure, if this is my thing I measure, you know 83 [degrees], is that's going to come back and hit this [another feature on plan].

Here, Ms. Lane directly told her students that the angles of incidence and reflection should be the same, but that the angle of refraction would be different, both concepts that they had learned about earlier in the unit. She also talked with them about how these concepts would affect their design. Sometimes, examples of this code consisted of the teacher working to overcome misconceptions that students had about the science or mathematics content. For example, one of the teams in Ms. Stone's class planned to use a plastic sheet on the bottom of their cooker container based on a misconception they held about the difference between radiation and conduction. Ms. Stone had the following conversation pointing to the students' misconceptions:

Ms. Stone: Why did you pick a transparency for the bottom?

Sophie: It makes more heat, radiation.

Ms. Stone: And, so if it's on the bottom, will it pick up very much radiation? Or is that going to be conduction?

Simon: Probably be conduction

Ms. Stone: Conduction?

Sarah: Wouldn't white felt kind of work because it would bounce off and reflect it?

Ms. Stone: **White felt would reflect radiation but if you're, if you're, so think about your cooker** [makes box shape with hands] **and think about the box. So your cooker's going to be sitting on top of the heat pad, right? What type of heat transfer is going to go through the heat pad?**

Simon: It's going to go up [points up].

Ms. Stone: **It's going to go up and what type of, what type of heat transfer is that? Is that going to be radiation or conduction?**

Sarah: Conduction

Ms. Stone: **Conduction. So what materials conduct well?**

Sarah: Black.

Ms. Stone: **Black absorbs radiation.**

Steve: Metal

Ms. Stone: **Metal. So you might want to think about the bottom.**

In this example, the teacher first elicited students' ideas about their design and the science behind their ideas. She first got feedback from them about their ideas, noticed the misconception about conduction and radiation, and talked to them about their ideas to help them better understand the differences between the types of heat transfer.

Examples coded as *science and mathematics* helped reinforce the science and mathematics ideas from the unit. They also gave support to the students as they were transferring their knowledge about science and mathematics from the activities earlier in the unit to the new context of their design project. During these conversations, the teachers needed to assess their students' understandings of the science and mathematics concepts and give support as needed.

3.4.7 Items coded as other

Most of the words coded as other were not directly relevant to the engineering aspects of the course, with the exception of those coded as *relationships outside of classroom* and *teacher as student.* Examples of each of these were not common, there were only six interactions that included references to *relationships outside of classroom* and only two interactions that included words coded as *teacher as student.*

Relationships outside classroom included any times that the teacher directly referenced students' knowledge that was relevant to the problem from their experiences outside the classroom. For example, while students were planning how to keep the GMO and non-GMO crops from cross pollinating, they were considering building an artificial barrier. They said:

Robert: How much would it cost to put up an artificial barrier?

Mr. Reed: Say…OK let's say if you're going to put an artificial barrier around a whole field. Rick, Rick? [Rick is in a different team].

Rick: What up?

Mr. Reed: **Corn farmers around here usually have how many acres?**

Rick: I don't know.

Mr. Reed **What would you say? Ryan, corn farmers around here usually have how many, on average, usually have how many acres?**

Ryan: I don't know.

Mr. Reed: **What would you say, 5, 10?**

Ryan: Well we [my family] have 7,000.

Mr. Reed: **7000 acres?**

Ryan: Yeah

Mr. Reed: **OK.**

Ruth: My dad has 1000.

In this example, rather than directly telling them the answer to the student's initial question, the teacher asked them to think about it, pulling in knowledge from different places, including their family life. This example pointed to the importance of the problem they were working on and connections to the relevance of engineering to their own lives. However, examples like this one were rare.

Mr. Reed was the only teacher that had talk coded as *teacher as student,* and these examples occurred during two interactions, both of which occurred while students were working on computers to make presentations for their client. One example was:

Roy: I don't know how to put it [my flowchart] on Google slides.

Mr. Reed: OK. Ryan, do you know how to get the arrows?

Ryan: I know how to get everything.

Mr. Reed: **Alright,** [to Roy] **you got to put the arrows in.** [To Ryan] **So can you come over** [to help us]?

In this example, the teacher asked one student to help him and another student with a particular point on the presentation, making arrows for the flowchart the student is making. In this example, the teacher put the student in the position of being the expert and asked the student to share their expertise with the teacher and the rest of the team. Examples of this code were rare; there were only two instances.

This section has presented examples of teacher talk from each code during conversations between teachers and teams of students. These examples represent illustrative examples of how the teachers talked to their students throughout the design process.

3.5 Discussion and Implications

The teachers in this study used their talk effectively in a variety of ways. They utilized many productive talk strategies that have been employed in science education and applied them to the new context of engineering. For example, the teachers modeled the four essential science language tools described by Dawes (2004): talk awareness, key questions and reasoning, active listening, and joint decision making. Their promotion of *talk awareness* was demonstrated by the large amount of interactions they had with teams, showing "the high value of group talk" (p. 685). Although the teacher's styles of interactions varied, they all let their students speak and listened to their students during the interactions, allowing the students to practice their communication with their teacher and peers. The teachers used "key questions and reasoning" throughout their talk, such as in the examples coded as *follow-up, critique*, and *ask for justification*. These codes usually involved key questions that the teachers asked to students to prompt deeper reasoning about their ideas. The teachers spent a significant amount of their talk employing "active listening," especially in examples such as those coded as *prompts to elicit student ideas* and *check on progress*. By asking their students to talk and using their own talk to indicate that they were actively listening, the teachers gave the students opportunities to be heard and modeled the importance of listening. The teachers also helped their students develop "joint decision-making skills" in ways such as the examples coded as *prompt student decisions*. These examples made it explicit to the students that they needed to work with their team to make a joint decision and follow through with that decision. The teachers also used strategies identified by Hofmann and Mercer (2016). They used the strategy of "making reference to ground rules [and] focusing on task" with examples coded as *clarify criteria and constraints* and *problem scoping*. They used "inviting [students] to speak, active listening, [and] repeating relevant ideas expressed by students" with examples coded as *prompts to elicit student ideas*. They used "probing and exploring students' understandings, encouraging students to compare and test ideas, [and] identifying resources for thinking" (Hofmann & Mercer, 2016, p. 412), such as with talk coded as *follow-up* and *science and mathematics*. The teachers let their students use their everyday language, while also encouraging their use of scientific language, which may have allowed them to better express and justify their ideas and use evidence in their arguments (Blown & Bryce, 2016; McNeill & Pimentel, 2010). The teachers' abilities to model these essential language tools point to their skills as teachers and their abilities to transfer these skills to a new context. Even though these teachers had limited engineering experience prior to their implementation of these units, they were able to take their pedagogical knowledge and use it in a new context and discipline to effectively support their students' teamwork during engineering design.

The teachers in this study had a lot of good conversations with their students about design. Throughout the design project, they talked with their students about their ideas in ways that allowed students to practice explaining their ideas, gave students different perspectives to consider in their design, and allowed the teachers to formatively assess their ideas. During discussions, the teachers asked about students' ideas and let students develop many of their own ideas. For example, in many of the examples of talk coded as *prompts to elicit student ideas* or *follow-up,* the teachers seemed to genuinely listen to and consider students' ideas, providing opportunities for the students to practice explaining their ideas, but also conveying the message that the students' ideas were important and mattered. Additionally, the teachers made points to *prompt student decisions* related to their design. These examples gave students opportunities to practice explaining their ideas and engage in conversations about their design ideas to practice talking like engineers. Often, the teachers tied in the science and mathematics aspects of the unit, helping students make important connections between subjects, which is a key goal of STEM integration (EL-Deghaidy et al., 2017; Moore et al., in press; Myers, 2015). Additionally, as these interactions were on a teacher-team level, the teachers were able to capitalize on their personal relationships with students and tailor their talk to the needs of the students, which has been linked to higher levels of student learning (Cazden, 2001; Gablinske, 2014). The examples presented in the results section provide evidence of the high level of conversations that the teachers and students were able to have using science integrated with the engineering design process.

However, when students started to struggle, especially with their design ideas or their team relationships, the teachers were quick to offer more direct support or an answer to the struggle. This pattern is shown, for example, by the examples of *critique* and *directly suggest ideas*, in which the teachers gave direct support while the students were struggling with their design ideas, and the examples that included the teacher *directly suggest[ing] ideas* immediately before they said something to *prompt student decisions,* in which the teachers sent mixed messages about who had control of the ideas and limit the scope of how students think about the design (Dong et al., 2015). By only superficially giving control to the students or by giving students strong hints or answers to their challenges, the teacher took away opportunities for their students to learn from the struggle with their ideas or failure of their ideas, which is an important part of learning to solve complex problems (Warshauer, 2015). One potential reason for this support is that the teachers may have be reluctant to remove support for fear of their students "getting stuck" (Hofmann & Mercer, 2016). Additionally, Vezino (2019) found that "the goal for teaching engineering, while a powerful upward force in itself, may not be a strong enough force alone for all teachers to enact a lesson that maintains a problem space with opportunities to face uncertainty" (p. 140). An implication of this study is therefore that teachers may have to use more strategies to encourage learning from failure and struggle. Maltese et al. (2018) identified several such strategies from their work with experienced maker educators, including that teachers can "model troubleshooting behavior," "minimize strong emotional response to 'normalize' failure," and "resist the urge to step in and directly fix something for youth" including "suggest[ing] they seek out assistance from peers or online before providing direct assistance" (p. 123). There were many missed opportunities throughout the teacher-team interactions in this study for the teachers to use these strategies with their students on a personal level.

Each of the teachers in this study had different teaching styles. Although they each had examples of talk that fell into several different types of codes, they had different strengths and areas that they emphasized. Additionally, many of the teachers did not discuss certain aspects of engineering with their students. For example, Mr. Smith was the only teacher to discuss trade-offs with his students, and Mr. Reed was the only teacher to have talk coded as *build engineering identity* and *relationships outside classroom.* Therefore, these results support that students need exposure to multiple engineering design experiences from teachers with different styles so that they can experience different types of engineering design experiences and benefit from the strengths of different teacher styles (Guzey, Harwell, et al., 2017; Liesveld et al., 2005). Additionally, when the students sought validation for their ideas, the teacher was often the one to give it, such as the examples coded as *critique* and in examples in which the students tested and demonstrated their ideas for the teachers before anyone else. In order to authentically practice engineering, students need opportunities to receive validation not just from their teachers, but from their peers, clients, and other stakeholders (Ballejos & Montagna, 2011; Nicol et al., 2014; Orsmond et al., 2013).

Although the teachers talked to their students about their design ideas and specific points of the engineering design process, they were less comprehensive in their talk about the design process as a whole. There were few examples of talk coded as *overall design process*. The lack of holistic discussions about the design process indicates that the students did not have support from their teacher to develop understandings of the engineering design process more abstractly, which may limit students' ability to transfer their design skills. The lack of talk regarding the overall design process could be an indication that the teachers did not thoroughly understand the engineering design process themselves. This finding is in line with Mesutoglu and Baran (2020) that found that during middle school teachers' first experiences with engineering design professional development programs, they are more likely to see engineering design as a linear process and see the design process as having a limited number of steps, and Meyer (2018) that found that after their first professional development experience, teachers had general, nonspecific ideas about the engineering design process, but were not confident in their abilities to integrate teaching the engineering design process into their teaching. However, follow-up professional development and further experience with engineering design can improve teachers' understandings of engineering design and the ways that they use their language to support students (Diefes-Dux, 2014; Duncan et al., 2011; Soysal, 2018). This finding has implications to support continuing teacher professional development to further their understandings of engineering design.

Although the teachers talked extensively with their students about their design ideas, they were less comprehensive in their talk about other areas of engineering. For example, talk that fell into the codes *discuss[ing] tradeoffs* and *learn[ing] from failure* was limited to only a few examples from one teacher. Both of these aspects are essential for learning engineering design and need emphasis to learn and practice engineering authentically (Crismond & Adams, 2012; Goldstein, 2018; Marks & Chase, 2019; Moore, Glancy, et al., 2014). Additionally, there were other aspects of engineering that were missing from any of the teachers' talk, such as ethics discussions, which is an essential aspect of engineering education (ABET, 2018; Barakat, 2011; Hess et al., 2017; NAE, 2004). These missing pieces may indicate that the teachers had less understanding or less understanding of the importance of other aspects of engineering outside of design. This finding points to the need to emphasize other aspects of engineering to teachers as they are learning to teach engineering.

Additionally, the teachers made very few references to larger goals of precollege engineering education, such as *build engineering identity* and *make connections* to students' lives outside of school, which are essential aspects of successful precollege engineering education (Kloser et al., 2018; Moore, Stohlmann, et al., 2014; Pantoya et al., 2015). Only one teacher had any examples of either of these codes. This gap has implications for students' conceptions of engineering and potentially their motivation to pursue engineering as a career. If students only learn about engineering in the limited context of a single unit and do not make connections to their identities or their lives outside of their science classroom, they are less likely to see themselves as future engineers or to develop a strong understanding of how engineering is relevant to their lives (NRC, 2012; Stevens et al., 2008; Wilson-Lopez et al., 2016).

Another important point that was largely absent from the teachers' talk was meaningful discussions around teamwork. When teams disagreed, the teachers responded with very specific and limited use strategies for working together, such as how to notate different students' ideas in a plan or how to agree on cutting materials. Although these strategies did help the students in the moment, they did not necessarily help students learn more about working in teams. The teachers did not take full advantage of teachable moments to help students learn to explain their ideas to their teammates, use evidence to argue for their ideas, and reach compromises with their teammates, all of which are important learning objectives of pre-college engineering education (Cross & Clayburn Cross, 1995; Mathis et al., 2016; Moore, Glancy, et al., 2014; Wendell et al., 2017).

The teachers in this study used their talk effectively in a variety of ways, espousing many talk strategies that have been shown to be effective in science and mathematics education literature. They also expanded on these ideas to incorporate talk strategies that outline different levels of support of students' ideas. For example, the design ideas code group encompasses four levels of support, prompts to elicit student ideas, follow-up, critique, and directly suggesting ideas, that provide a structure of different levels of support that teachers can use when interacting with teams of students during engineering design projects. When students struggled, the teachers often jumped in to provide answers to their struggles, such as when the students had disagreements with their teammates, they usually gave a resolution to the argument, rather than supporting the students through a conversation to learn to resolve the issue. Although the teachers had many conversations with their students about many areas of engineering, including discussing design ideas, decision making, and justifying ideas, there were other areas of engineering, including discussion trade-offs, learning from failure, and connecting engineering to the students' lives outside the classroom that were underemphasized in the teachers' talk.

3.6 Conclusions

This study examined the teacher-team interactions of six teachers during engineering design projects. The results indicate that the teachers had conversations with the students about many areas of engineering. The examples demonstrate that middle school students can have high level conversations with their teachers about their design ideas supporting that teachers should have high expectations for their students and expect them to be able to communicate their ideas. However, when students struggle to communicate their ideas, the different levels of support outlined in the coding framework and examples provide a structure of support.

There were many important areas of engineering that the teachers only exposed their students to in limited amounts or not at all. Few of the conversations involved talk about important components of engineering education such as learning from failure, effective teaming strategies, learning to balance tradeoffs, and connecting the engineering design experience to students' lives outside the classroom. The teachers gave their students many opportunities to talk about their design ideas and often asked insightful questions to follow-up on their ideas. However, when the students struggled, with their design ideas or with teaming, they were quick to jump in with a solution. For the teachers in this study, this unit was their first experience learning and teaching engineering design, so it is commendable that they were able to support their students through many important aspects of engineering. However, if this unit is the only experience students have with engineering design, there are broad repercussions. If students do not have other experiences with engineering, they will not get a full picture of what engineering is before either choosing to pursue an engineering career or opting out of engineering. This study also has implications in teacher professional development. The teachers in this study put effort into providing their students with a high-quality learning experience and engaged in the professional development they had access to do so. However, in order to more authentically teach engineering, they need the support to develop further understandings of engineering and to learn how to support their students in different ways.

Future work should examine the effects of teacher-team interactions during engineering design after the teachers have more experience with engineering and further professional development. Additionally, future work could focus on the effects of different kinds of teacher-team interactions on students learning and attitudes towards engineering. Further research could focus connections across teacher-team interactions and whole class discussions and lectures and how they support each other.

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4. PROFESSOR TALK IN UNDERGRADUATE, INTRODUCTORY DESIGN: A MULTIPLE CASE STUDY FROM MECHANICAL AND BIOMEDICAL ENGINEERING

High quality instruction is not only essential for student learning, it is also an important aspect of retaining students and engaging their interest in STEM fields (Engberg & Wolniak, 2013; Marra et al., 2012). Low quality teaching of undergraduate engineering students leads to frustration, dissatisfaction, and struggle with engineering, especially for underrepresented groups in engineering (Blair et al., 2017). The first year of college, as students are introduced to the discipline of engineering, is an especially key time to introduce students to engineering in positive and realistic ways that will set them up for future success (Froyd et al., 2012). Specifically, the ways in which students interact with their professors have been shown to influence students' perceptions of engineering and their persistence in STEM disciplines (Jones et al., 2014; Watkins & Mazur, 2013). However, the most effective ways for professors to interact with students during engineering design are not well understood. Therefore, in order to better understand effective teaching strategies during undergraduate introductory engineering design courses, this study examines one aspect of pedagogy, professor talk, to address the research question: How do instructors interact with students and use their talk as a tool to scaffold undergraduate students' learning during their work on engineering design projects in introductory engineering courses?

4.1 Background Literature

Introductory undergraduate engineering design projects have an important role in introducing students to the field of engineering and framing their learning experiences. Instructors' roles in design projects have unique challenges and the ways in which teachers talk to their students frame their design experiences and learning.

4.1.1 Introductory Engineering Design

Introductory engineering design courses, sometimes called first-year design or cornerstone design, play an important role in introducing students to the field of engineering (Froyd et al., 2012). Since their resurgence in the late 1990s, many engineering programs include introductory design experiences (Burton & White, 1999; Courter et al., 1998; Dally & Zhang, 1993). These design experiences take on many different forms, including courses focused solely on design and courses with design as one piece of an introductory course. Students enter college and introductory engineering courses with vast arrays of experiences, interests, and ways of knowing, from both their formal and informal education, which affects their conceptions of engineering, how they define and contextualize problems, and their academic preparation (Kilgore et al., 2007). These prior experiences provide students with some knowledge about engineering design processes "that course design experiences can hook into, and upon which students can build more sophisticated understanding" (McKenna, 2007, p. 733). However, early design experiences have direct effects on students' design thinking, how students prioritize components of engineering design, and their conceptions of engineering (Jones et al., 2014; Williams et al., 2011). Additionally, introductory design experiences are correlated with increased intellectual and cognitive development and retention (Knight et al., 2007; Marra et al., 2000). Reasons for these positive effects likely include "active hands-on pedagogy, creation of student learning communities, an early experience of the human side of engineering, self-directed acquisition of knowledge by students, instructor mentoring, and the success orientation of the course" (Knight et al., 2007, p. 11). However, the extent of the effects of each of these factors and how to implement them into classrooms is not well understood.

Many studies have been conducted comparing the design processes of first-year engineering students to more experienced students and to expert designers (e.g., Atman et al., 2007; Atman, Cardella, Turns, & Adams, 2005; Crismond & Adams, 2012). These studies have shown that although first-year engineering students enter college with some understandings of engineering design, when compared to more experienced students and experts, first-year students do not use design processes that are as sophisticated as more experienced designers. For example, novice designers often do not spend as much time on problem definition, are not as reflective in their design processes, and do not use as much evidence to define their decisions (Adams et al., 2003; Atman et al., 2005; Crismond & Adams, 2012; McKenna, 2007). Beginning designers often can become fixated on an idea early in the design process, limiting the scope of their brainstorming (Crismond & Adams, 2012; Gero, 2011). Additionally, compared to more experienced designers, first-year students are not as reflective about their design practices and must learn to use skills such as self-monitoring, clarifying, and examining in order to learn design (Adams et al., 2003). Although a variety of factors play into how students overcome these challenges over the course of their education, including some that are not within an instructor's power, instructors should be aware of these challenges to best support their students' learning in design so that they can tailor their instruction to helping students to improve their skills in engineering design.

4.1.2 Instructor Role in Engineering Design Education

Instructors play a vital role in helping to guide students towards more sophisticated design processes and developing their conceptions of engineering. Introductory design courses directly affect student's perceptions and "what instructors do in courses—and not simply the content—can affect students' domain identification. This issue is particularly crucial in cornerstone courses because these courses are often students' first window into engineering" (Jones et al., 2014, p. 1350). Many courses that first-year engineering students take are focused on analytic, well-structured problem solving, rather than open-ended design. Therefore, it is an additional challenge for instructors of design courses to support students in their thinking across these different types of problem solving (Lande & Oplinger, 2014). There has been limited research on the specific ways to support students in the classroom-based projects that are typical of first-year design courses; however, there has been research on pedagogies and instructor roles in other contexts of teaching design, such as senior level design reviews, that can be used as a starting point to improve understandings of how instructors can support their students during engineering design projects.

One important role of the instructor is to act as a mentor or guide to students as they are working on design projects (Paretti, 2008). Several studies suggest that for students to authentically engage in design, instructors should act more as "coaches" or "tutors," rather than the perfect expert in the classroom (e.g., Dannels, 2002; Oak & Lloyd, 2015). McDonnell (2016) found that when working with student designers, an experienced designer who acted as a tutor played a role that "act[ed] as project manager and inculcate[d] them [the students] as to what a systematic design process entails for a designer" (p. 17). That study also found that an experienced design professional gave students very structured tasks but pushed them to make their own design decisions. Additionally, the designer gave them direct support of technical knowledge and made references to precedent designs. Some common challenges related to mentoring students in design include balancing teaming and team dynamics, focusing on the final product versus supporting learning of the design process, and balancing technical practice with professional skills practice (Paretti et al., 2011). However, "the strategies and skills needed to effectively guide and mentor students as they develop into practitioners can differ significantly from those needed to help student develop content mastery, and currently little work has been done to explore and describe such strategies and skills" (Pembridge & Paretti, 2010, p. 9).

Another important role of the instructor in introductory design projects is to support students to overcome challenges in design, such as those typically experienced by beginning designers (Crismond & Adams, 2012). For example, one such challenge is overcoming idea fixation and learning to effectively brainstorm. Sio et al. (2015) found that when instructors provided examples, students were able to generate more example-related ideas and higher-quality ideas. However, providing examples also limited the number of categories of student ideas. Additionally, in order to learn design, students must be exposed to both the knowledge about design and gain experience with the skills needed for design (Christiaans & Venselaar, 2005). Therefore, the instructor should provide experiences that allow students to progress through the entire design process and apply different types of design knowledge.

Since first-year engineering design courses are often students' first experience with engineering design, instructors of introductory courses have a role to provide an authentic experience that gives students accurate pictures of what engineering design is. Instructors of these courses also have a role in helping students see themselves as engineering designers and gaining confidence and identifies around engineering design. In order to develop students' engineering identities, instructors should, for example:

> design their instruction to empower students with choices and decisions, explain the usefulness of the material, ensure that students who put forth effort feel that they can succeed, interest students in the material, and show that they care about students' academic success (Jones et al., 2014, p. 1350).

The ways that teachers carry out these activities in their classrooms is structured by the ways that they talk to their students.

4.1.3 Professor Talk and Design

Teachers play an important role in how students develop their knowledge and think about problems. Specifically, how students learn design thinking and doing is a gradual process in which communication in essential, including communication between teacher and student (Fleming, 1998; Schön, 1983). The ways that teachers approach teacher-student communication and the things they say to their students influence how students design. For example, if an instructor proposes a solution to a design problem, students often take that as advice and tend to follow it, limiting the scope of their potential solution (Dong et al., 2015). On the other hand, "positive criticism can also have the unintended consequence of leading students to believe that they have already identified the best solution, which dissuades them from additional exploration" (p. 89). Therefore, instructors must be careful in both their positive and negative comments on designs. Additionally, the ways that the instructor uses talk to set up the classroom and design challenge affect students' design processes. For example, in giving specific instructions related to problem framing, the instructor influences how students think about design as either a piecemeal of smaller activities or as an integrated design process (Secules et al., 2016). When "the language of engineering design...is oriented to the design process," rather than the solution itself, students more clearly see the importance of engineering design as a process, "rather than knowing engineering design as a set of solutions to a problem with few or no events in between" (Atman et al., 2008, p. 318). Therefore, instructors have the careful task to monitor what they say to match the needs of the students at the time of the interaction.

4.2 Theoretical Framework

This section describes the theoretical framework used to guide the analysis of the professors' talk. The theoretical framework on a foundation of the work of Vygotsky (1978, 1986). Engineering students learn the process of design and ways of engineering thinking through support from their teachers and peers. Teachers act as a more knowledgeable other in the classroom, guiding and scaffolding students towards development of skills and knowledge needed to understand concepts that they cannot do alone. Teachers use a range of pedagogies to support their students, which are framed by the way their use their talk to portray ideas to their students. Although teachers face many challenges in developing their scaffolding, effective scaffolding is contingent on students' current needs, fades over time, and transfers the responsibility for learning gradually to the students. Each of these components are described in depth in the following paragraphs.

Teachers play a vital role in guiding their students to develop their understandings of concepts and move towards understanding higher level concepts. Instruction by a more knowledgeable other is essential for guiding students to more and more difficult problems that they could not do on their own (Vygotsky, 1978, 1986). In his studies of young children, Vygotsky described how a child's concepts about complex processes that are outside of the child's everyday experiences are supported by instructions from an adult, resulting in them understanding and using concepts that they would not normally be able to understand just from their everyday experiences. Although Vygotsky's work was focused primarily on younger students, these same ideas apply to the early undergraduate level students that are the focus on this study. Just as Vygotsky found in young children learning about the world around them, engineering students also encounter many concepts that are not directly observable in their everyday experience that would lead them to an intuitive understanding of engineering phenomenon (Streveler et al., 2008). However, instruction on how to conceptualize ideas can support students in developing higher levels of understandings (Slotta & Chi, 2006). Additionally, there is a direct analogy between the ways that Vygotsky describes students developing early skills to engineering students as they learn and practice the activities and concepts of engineering. Just as young students are learning the language and concepts of their parents and communities, engineering students are learning the language, practices, and concepts of the community they are entering: engineering (Atman et al., 2008; Johri et al., 2014).

Teachers use many different pedagogies to support their students' learning in the classroom, encompassing all of the activities, structure, and content of their classes. However, these activities are framed and supported by what the teacher says. Therefore, what the teacher says frames all interactions and activities that teachers use to scaffold their students, and we cannot understand the most effective ways to support student engineering learning until we understand effective ways to frame the scaffolding provided to students (Scott, 1998). In other words, understanding effective pedagogies for teaching engineering starts with understanding effective ways to talk to students.

There are many different ways that teachers can use their talk to scaffold students. In a literature review spanning eleven years of empirical studies (66 studies) that focused on scaffolding as defined by Wood et al. (1976), van de Pol et al. (2010) found many differing ideas about scaffolding. However, they identified three major components of scaffolding that the research is consistent on. First, there must be *contingency*, meaning the teacher's support must be adapted to the student's level. Second, there must be *fading*, by the "gradual withdrawal of the scaffolding" through decreasing "the level and/or amount of support" over time. Finally, there must be *transfer of responsibility*, "that is, responsibility for the performance of a task is gradually transferred to the learner" (p. 275). Even within these three overarching aspects of scaffolding, there are different forms. Sharpe (2006) synthesized work across different types of scaffolding, defining two different types of scaffolding: 'designed-in scaffolding' involving "the overall design of the unit of work to achieve specific outcomes including the sequence of tasks within each lesson and types of resources to be utilized," and 'contingent scaffolding,' that is "contingent on the circumstances" and refers to when the teacher takes advantage of point-of-need opportunities, using "a variety of discourse strategies such as questioning, recasting or relating to students' previous experiences" (p. 213) to interact with students in the moment.

Teachers face many challenges when using their talk to scaffold students. One of the key aspects of scaffolding is the timing of the support (Vygotsky, 1986). There are certain periods of optimal learning that teachers can capitalize on because "during that period an [instructional] influence that has little effect earlier or later may radically affect the course of development" (p. 189). Instructors have to assess their students to figure out when this ideal time is and figure out how to support their students to take advantage of this period (van de Pol et al., 2014). Additionally, teachers must balance the technical content instruction with the language instruction needed to support the concepts and if language used in scaffolding is too narrow, it may limit the students' abilities to transfer their knowledge to new contexts (Jung, 2019).

The ways that professors talk to their students set up the scaffolding to introduce students to disciplinary language and ways of thinking to understand concepts that are in their zone of proximal development. This study utilizes this theoretical framework to examine the talk of three professors during introductory, undergraduate engineering design projects. Each case study is framed around the specific talk strategies each professor uses and the cross-case synthesis looks holistically across the cases using the theoretical framework.

4.3 Methods

4.3.1 Approach

This study uses a multiple case study approach (Creswell & Poth, 2018; Yin, 2018) to look at the talk strategies of professors of undergraduate introductory engineering courses during design projects. The purpose of case study research is to develop an in-depth description of a bounded system, which must be a case or cases that are chosen with purpose. The cases in this study were chosen to represent engineering professors who engage in varied types of verbal interactions with their students, including but not limited to discussions with the whole class, interactions with individuals and teams of students, and questions asked by both the professors and students. The analysis and written descriptions of each case cannot be separated from its context, so case studies use multiple sources of information, including interviews, observations, and documents, to develop these descriptions (Denzin & Lincoln, 2018). In this study, each bounded case is the classroom talk of a professor during engineering design projects. Case study methodology has been used in other contexts to study communication between instructors and students in design (e.g., Paretti, 2008). Each descriptive case study (Schwandt & Gates, 2018; Yin, 2018) focuses on analyzing data from all aspects of the case to provide an in-depth description of each of the three cases of professors' talk interactions with students during engineering design projects along with a cross case synthesis across the cases.

4.3.2 Context

This study was conducted at a large, public university focused on undergraduate teaching in the western United States. The College of Engineering at the university has the largest enrollment with 6,000 students, of which 83% are in-state students and 1% are international students. The student body is 55% white, 17% Hispanic/Latino, 13% Asian American, 8% multi-racial, 4% unknown/other, and less than 1% each African American and Native American. 48% of the students are women and 52% are men. 20% of students receive Pell Grants. For first-year students, the College of Engineering has a 23% acceptance rate and the university has an 82% six-year graduation rate. The size and gender demographics of each class focused on in this study are presented in Table 4-1.

Table 4-1. *Demographics of each professor's class*

Professor	Engineering Discipline	Total number of students	Percentage female students
Davis	Mechanical	23	39%
Pfeiffer	Mechanical	23	30%
Wilson	Biomedical	30	53%

Cases

This study focuses on three professors, Professor Davis, Professor Pfeiffer, and Professor Wilson, all pseudonyms, who each taught introductory courses for their disciplines that included the students' first experience with engineering design at the university. Two of the cases were mechanical engineering professors and the third case was a biomedical engineering professor. Purposeful sampling (Creswell & Poth, 2018) was used to choose each case, selecting professors who use active learning pedagogies that included different types of student-teacher interactions. Each of the three professors have different experiences and ways of teaching. This section presents a brief description of each case, utilizing quotes and information from their pre-interviews. Further descriptions of each professor's experiences and teaching views are included in the results section along with examples from their teaching that tie into their experiences. Demographic information for the three professors is displayed in Table 4-2.

Table 4-2. *Demographic information for each professor*

Professor	Years of teaching experience	Rank at the university	Gender	Ethnicity	Native Language
Davis	>20	Professor	Male	White	English
Pfeiffer	>8	Assistant Professor	Male	White	German
Wilson	>5	Assistant Professor	Male	Black	English

Professor Davis is a professor of mechanical engineering with more than 20 years of experience teaching at the university. He is very involved in the department and university, which is demonstrated, for example, by his service as the mechanical engineering department chair for 6 years. Prior to teaching, he worked in the aerospace industry for six years, as an engineering designer and in structural analysis. Additionally, he is an alumnus of the program in which he is teaching. Professor Davis has a lot of experience teaching different types of design, including the first-year course studied in this study, but also the junior and senior level design courses in the department. When he first began teaching, he took "just a few classes through the Center for Teaching and Learning. When I first got here in the first two, three years, I did take a couple through them" that covered "a lot of the basic things, even just writing things on the board, making sure people could understand them. We talked a lot about getting feedback from the students in class." He has had no other formal teaching education.

Professor Pfeiffer is an assistant professor in mechanical engineering. He has been at the university for five years and has taught the first-year course included in this study three times, as well as many of the courses for the heating, ventilation and air conditioning (HVAC) concentration, including the senior design course for the HVAC concentration. Prior to working at the current university, he taught similar courses at a different university, which he had entered directly after receiving his PhD. In graduate school, Professor Pfeiffer took extra steps to earn two Graduate Teacher Scholar Certificates that required him to teach classes, “implement something new in the class, and then analyze it, assess it afterwards,” take several hands-on teaching workshops, and mentor other teaching assistants. He has continued to take workshops at each of the universities he has taught at to improve his teaching. English is not Professor Pfeiffer’s first language.

Professor Wilson is an assistant professor in biomedical engineering. He has taught at the university for 5 years. Prior to that, he had extensive experience in industry with several large medical device and chemical companies. He also “started a company with one of my classmates from business school and we designed a product that’s in clinical trials right now.” Throughout his career, he had opportunities to teach short courses and modules in several different contexts. When asked about his teaching education, he said “all my coursework has been engineering and business […] I went through training to teach and facilitate their [an organization he worked with] classes. But other than that I never, come to think of it, I haven’t had a teaching class.”

Mechanical engineering course format

The format for the mechanical engineering courses taught by professors Davis and Pfeiffer was similar across the classes. Each class met once per week in a small lab section (24 students or less) for three hours. Additionally, a larger seminar (90 students) met once per week for two hours. Although professors Davis and Pfeiffer each taught multiple lab sections, this study focused on one of their lab sections each. Each professor taught multiple lab sections. The two sections focused on in this study were taught on different days, but at the same time of day and in the same classroom. Professor Pfeiffer was the instructor for the seminar class, however, during the design project, Professor Davis visited or taught the seminar class most days that the students were engaged in the design project.

For the design project, each mechanical engineering class had a similar format. For both mechanical engineering classes, the design projects were conducted entirely during class time, with the exception of the initial homework assignment. The deliverable for the project was a poster that was presented at a design expo on the final day of class and evaluated by the students’ peers. The design project was developed primarily by Professor Davis with input from Professor Pfeiffer. In addition to the major design project that is the focus of this study, each class engaged in a short design project to build a spaghetti tower on the first day of class. These class periods were not recorded because it was not possible to have student consent on the first day of class.

The design project was introduced in the lab sections with a homework assignment in which students were given the design problem, asked to brainstorm at least four potential ideas, and complete a skills self-assessment. The skills assessment asked students to rate their skills in creativity, leadership, organization, communication, and artistic ability. The design challenge that the students were given was:

> We are asking you to design something that could help people with physical challenges to improve their accessibility to some activity. It will be up to you to identify the physical challenge and the activity you are addressing. Example: Design of playground equipment to increase accessibility for people that use wheelchairs.

The students were given a graphic of the engineering design process and asked to complete the first two steps individually with the following prompts:

> ASK: Do you understand the problem at hand including the objective and the constraints?
>
> IMAGINE: You are to contemplate the challenge, think about possible solutions. You want to generate as many solutions as possible. Do not evaluate yet! If one of your ideas does not include a nuclear reactor you're probably not getting crazy enough! Now filter down your ideas to the best ones that you will develop further and write up for class.

During the subsequent lab meeting, the students got into teams based on their ideas, each professor used a different method to form teams. During this same lab period, they worked with their teams to prototype their ideas. In both classes, they were asked to continue to consider multiple ideas.

During each of the following two seminar sections, the students had one hour to work with their team on their design projects, however they chose to use the time. Finally, students had the entire last seminar and lab sections of the term to work on their projects resulting in a total of 10 hours of class time devoted to the design project. During the final meeting of the course, there was a design expo in the format of a poster session.

Biomedical Engineering course format

The biomedical engineering design project was conducted as a small part within an introduction to biomedical engineering course. This course was taught primarily to sophomore students but was the first engineering design experience in the Biomedical Engineering curriculum at the university. This course met once per week for one hour and the purpose of the course was described as "introduce the fundamentals of bioengineering design. Some areas of discussion will include biomechanics, biomaterials, pharmaceutical and medical device design, cardiovascular disease, and intellectual property." Most class periods focused on particular topics within biomedical engineering practice. One of these class periods focused on the design project, students were expected to complete the rest of the project on their own time. Their design projects were very open-ended. They were asked to come up with an idea to solve a problem within biomedical engineering, without any other constraints.

During the class period in which the students worked on the design project, Professor Wilson introduced the project by giving an example of a senior design project. He then used this example to walk the students through the design process and described which parts of the more thorough senior design project they needed to do for their smaller design project. They were then given graphic organizers to organize three different ideas. Outside of class, they were expected to continue with one of these ideas to produce a deliverable of a short presentation for a design expo. This design expo was conducted in a different course, Professor Wilson was not directly involved.

4.3.3 Data collection

The first step in the data collection process was to observe each potential case prior to the design project to better understand if there were sufficient opportunities for professor-student verbal interactions during the data collection period, to start to understand the classroom environment, ensure that the equipment worked, and explain the project to the participants and gain their consent. Additionally, before any classroom observations, each professor was interviewed to obtain information about their educational background, how much and what types of teaching experience they have, what teaching professional development they have had, and some information about their views on teaching style. The primary purpose of these initial interviews was to gain further insights into the professor's teaching and thinking to more fully understand and describe each case.

Classroom data were collected throughout the length of time that the students were working on the design project in class and consisted of video recordings of the classes, field notes, pictures, and interviews with the professors. The primary researcher attended each class with a video camera with a transmitter that allowed sound to come directly from the professor. The researcher sat in an inconspicuous location so as not to disrupt the class and recorded field notes throughout the class. The field notes recorded general notes about what happened in the classroom and time stamps for transition points for reference against the video recordings later. Additionally, key moments or aspects of the professor's talk were noted for later analysis as well as any questions for the professor and specific points of dialogue to probe further. After each class period, an informal conversation was conducted with the professors to ask these questions to better understand what the professor was thinking at the time and gain further information about the interactions. To aid in the development of the trustworthiness of the study, the data collection consisted of multiple sources of evidence, including video and audio recording, field notes, and professor interviews, saved in an organized database by backing up all data by saving in two different, secure locations and maintaining consistent naming conventions with all files, and a chain of evidence was maintained by keeping notes about the work (Yin, 2018).

4.3.4 Data analysis

The data analysis followed multi-case study procedures laid out by Yin (2018). Each case was analyzed individually, and then compared across the cases in a cross-case synthesis. This process was done using a deductive approach, as described by Yin (2018), based on the theoretical framework described earlier. Each case was first analyzed individually. For each case, the primary researcher "play[ed] with the data," "searching for patterns, insights, and concepts that seem promising" (p. 167). The analysis was done over a period of time. First, during the initial classroom observations, the researcher kept notes about key aspects of each professor's talk. These key aspects were briefly discussed by the researcher and the professor after each class period to confirm the professor's intention to focus on these aspects. Next, all the video recordings were transcribed. During the transcription process, the primary researcher continued to make notes and comments about common themes in each professor's talk. These notes and observations were used in conjunction with the theoretical framework and the transcriptions of the classes and interviews to write the description of each case. Finally, a cross case synthesis was written comparing and contrasting the salient aspects of each case. Throughout this process, member checking (Creswell & Poth, 2018) was used to ensure accurate representation of each professor's ideas and actions. Member checking was done through conversations with each professor after each class period, conversations with each professor throughout and after the data collection period and sharing the written drafts with each professor.

4.3.5 Trustworthiness

Each of the four principles of high-quality analysis described by Yin (2018) were used to ensure a high-quality, trustworthy analysis. The analysis *attended to all the evidence* by including all the professor's talk from the entirety of the time that students were working on their design projects and all the information from the interviews with the professors. Second, the analysis investigated *plausible rival interpretations* through conversations with the professors and between the researchers. Next, the analysis focused on *the most significant aspects* of the professors' talk, focusing on the aspects of their talk related to the theoretical framework in order to focus on how the professors used scaffolding, rather than on the many other aspects of pedagogy they used in their classrooms. Next, the researchers "demonstrate a familiarity with the prevailing thinking and discourse about the case study topic" (p. 199) through extensive literature review prior to the data collection and throughout the data analysis process.

4.4 Descriptions of Each Case

This section describes each case, Professor Davis, Professor Pfeiffer, and Professor Wilson, utilizing examples from their teaching and interviews.

4.4.1 Case 1: Professor Davis

Professor Davis teaches the first-year introductory mechanical engineering course. He is a storyteller who used a range of examples to set up a structure to his class. To him, an important aspect of his role as an introductory engineering professor is to help students develop passions for mechanical engineering and expose them to future supports and experiences in their education. Details about how he used his support in these ways are explained in this section.

Used storytelling to build the scaffolding

Professor Davis is a storyteller. When he uses his talk to convey ideas, answer students' questions, or emphasize a point, he does so with a story. As he put it:

> I just, and this is part of just who I am and the way I interact with everybody, but I just like to talk to people and talk about my life experiences and hear their life experiences and just get to know people as people.

This attitude has allowed him to develop and use different stories from a vast range of engineering and teaching contexts that he draws on in his teaching. This philosophy plays into much of his teaching, including the casual manner that he comports himself, or as he said in his pre-interview, "we are who we are, and I tend to be very casual. I don't have much of a, 'I'm the professor and you're the student' [attitude]."

Professor Davis used stories throughout the design project. These stories framed many of his interactions with his students and often built on each other to convey ideas through examples, rather than direct instruction. The following three examples demonstrate how Professor Davis used a series of stories to support students' learning about a major learning objective he held for the project. Professor Davis wanted his students to learn about improving their abilities to work in teams and to value different kinds of skills in their teammates. Instead of just telling his students this goal, on the first day of the design project he told several stories to the whole class, including the following:

Professor Davis: Another story. […] The way we generally work it [the structure of the senior design course], you assign the project to the team, you meet and then they kind of divide up the tasks. They meet with the advisor and they say, "OK, this week Jane's going to work on this, Chris is going to work on this, Fred's going to work on this." And I say, "great." So they go off for a week, we meet the next week we get together as a team. "Jane, how'd it go?", "Oh good. I did this and I looked into this." About halfway through Chris jumps in and says, "Yeah, you know, I looked at that also" and just kind of takes over and did twice as much as Jane, to be honest. He's brilliant. OK, we all see it now. Then he presents his stuff and it's excellent. And he does the same thing to Fred. Fred starts to present and Chris jumps in and says, "Oh yeah, but I looked into that too." A week later, what do Jane and Fred do? Nothing. Nothing. They're like, "OK, we got the crazy superstar, he's going to do the whole project. We don't really have to do anything." And it's a little embarrassing to walk into the meeting and get steamrolled like that. So it's everyone on the team's responsibility, right? To keep everyone invested in the

	project. So what Chris, what could have Chris done better? Look, he's going to look into it cause it's, he's just genetically incapable of not looking into everything.
Student 1:	Let the others present their ideas and what they found before.
Professor Davis:	Let them finish before? Even better than that. What could he have done?
Student 2:	Present what he's supposed to.
Professor Davis:	Present what he's supposed to. And I agree with you there, but what else could he have done? Yeah?
Student 3:	Show them what he had done on the research before the meeting.
Professor Davis:	Give it to Jane, right? Talk to Jane and say, "Hey, I also looked into that and here's some stuff I found. You may want to incorporate this into your presentation to Doctor Davis when we go in the meeting" and right. So then he's lifting her up right and now they all present and I'm super happy with everybody and everybody's learning.

Professor Davis continued this story with a specific example from a senior design project team he had worked with that included a student that was especially good at supporting his teammates:

> I would watch this group working for the whole year. They had the most fun. They did an excellent job. Everything was on time. The project was great, and I'd watch them together, and you could see him checking in with everybody. Sometimes verbally, sometimes not verbally. Just, "How you doing?", "Is everything going OK?", "Is your assignment going well?" He was the one that was kind of dealing with all his teammates for a year. Just making sure that everybody was happy. These are the kinds of things you, you think if you see someone like kind of fading out of your project and well "we asked them to do this and they didn't do it." It's up to the whole group, right, to say, "come on, you really need to pitch in."

These examples set up, at the very beginning of the design project, that in order to have a successful team, the students need to support their teammates. These stories also reinforce Professor Davis's point that he made several times that teams need a variety of skills and that technical knowledge is not the only thing a team needs to be successful. Later, on the last day that the students were working on the design project, a student came up to Professor Davis and said, "so one of our team members hasn't shown up and has not been helping out at all. […] He's been present. He just hasn't helped. We have a group chat, and he hasn't replied at all." After asking who the student was and checking that they had turned in other assignments to check if they were still in engaged in the rest of the class, he responded with several stories:

Professor Davis: My niece was homeschooled, all through high school, and she started college last year, this is her sophomore year. And right away, the first thing she was talking to her parents about was the group stuff. She's not used to it, and she doesn't like it. You know because she's just like, people don't show up and people don't…She's very responsible and it's always tough from the instructor's standpoint because, you know we have team based senior project now, that started 15 years ago, but it came from industry, that's what they want.

Student: My high school's actually really project-based learning.

Professor Davis: So, you've done a lot of it already. But it is something we spend, you know, we do think about. And you'll always, you know a lot of your labs are going to be team based. I had a design thing I was doing in Spain. And it was a graduate student from Penn State who was running it and I was talking to her. Well, I gave the speech in here about the super stars and you know, she was the one, she was the super star who basically turned her teams off because she wanted to do everything, you know? So, it is this balance.

In this example, he validated the difficulties of working with a team, but pointed out that it was a necessary thing for the students to learn to meet the expectations of the industries they were working towards joining. He also reminded the students of his earlier conversation and that it was part of their responsibilities as a teammate to support their peers. This series of stories demonstrated a typical scaffolding pattern in Professor Davis's class. He used stories from his experiences to give examples to the students about how they could think and approach problems. He never directly told them what to do but instead gave them many examples of how they could act and left it up to them to make the final leap in their zone of proximal development and make decisions about what they should do.

Scaffolded students' understandings about mechanical engineering as a discipline

Professor Davis holds the view that one of his primary roles as the teacher of the introductory mechanical engineering course is to help students understand their passions and to identify if mechanical engineering is one of these passions. This view was evidenced, for example, by the following comments he made with a team:

Professor Davis: To me, it's awesome that we have you guys declare as freshmen because we get to do this [class]. And we get to…I

	had two students doing a makeup lab last week, they're both switching out of ME.
Student:	Really?
Professor Davis:	Students always think, "Oh, you're going to try to talk me out of it." No, it's one of the reasons we do this.
Student:	It's like a little like trial period, right? To see what it's like.
Professor Davis:	Yeah. So one of them is going into industrial engineering. A lot of high school counselors and things don't know about industrial engineering. It's one that they graduate 130% of the students they bring in all the time, because they're just a net importer, because people don't pick it as freshmen, but it's a great career.

Many of his interactions with students served a purpose to scaffold the students' ideas about mechanical engineering to build on their knowledge of what is possible with mechanical engineering. His strategies of engaging in stories with his students help him both to share his own passion for mechanical engineering with them as well as help them identify their own passions. Many of his conversations with teams of students as they were working on their design projects consisted of just talking about aspects of mechanical engineering that they found interesting. For example, when the students were sharing their ideas with other students before they had formed teams, he overheard two students talking and interrupted their conversation:

Student 1	I saw one, and it was someone like strapped to the seat on the mountain bike, and it was like a [bike name] bike so the throttle [moves hand like a throttle]. And then he was like…
Professor Davis:	Two wheels?
Student 1:	What?
Professor Davis:	Two wheels? Like a bike?
Student 1:	Yeah, two wheels. It was like, he used to be like a really good biker, and he crashed and got paralyzed and he's like hitting jumps that are like this high [holds hands up about 4 feet off the ground]. Like on a [bike name] bike.
Professor Davis:	I knew a guy with MS that had a four-wheeler that he would strap in, and he'd lean forward, and he'd bomb. It had to be wide, like more dirt roads than single track, because he needed the width, but…
Student 2:	That's like the guy with the hoverboard with the wheelchair.

In a similar example, when students were prototyping their ideas with their teams, a different team started sharing one of their ideas with Professor Davis, saying:

Student 1:	So basically it's a hand held stick that allows users to mouse again, like a computer mouse. Basically, it has a high friction pad here so when you press down the mouse and you move alongside with it. No problem. And the way you click the buttons is very simple, you just twist your forearm. You just pivot off of this.
Professor Davis:	[mimics hand twisting] So, click, click, so right and left would be…
Student 1:	Yeah
Professor Davis:	Have you ever seen a foot mouse?
Student 2:	Wow, there's such a thing?
Professor Davis:	Oh, yeah, yeah. They have them now, it's tough, right?
Student 2:	That sounds so impractical.
Professor Davis:	You know, if you don't have a hand. Actually, a lot of people get carpel tunnel problems from too much mouse use and so it's not that they don't have a hand.
Student 3:	Have you seen those mouses where it's like a slide thing, and you go up. Like basically it's a tube and there's an outer thing [gestures with hand to describe shape] [Students and professor continue talking about different types of computer mouses.]

In these examples, Professor Davis encouraged the students to think about different applications of the designs, different potential users of the designs, and shared applications of mechanical engineering that he had seen benefit different people. These examples demonstrate how Professor Davis encouraged his students to think about different aspects of mechanical engineering and how these "cool" things could help people with a variety of needs. Professor Davis used conversations like these to take students' ideas and push them to think about things such as other aspects of the problem, other design criteria, or other potential solutions. In these examples, he modeled different ways to expand on the problem and potential solutions, using language that acted as a scaffold to students being able to think about different potential solutions to a problem themselves.

There is evidence in the students' conversations that they were listening and taking these ideas to heart. The following two examples show one example of this evidence using quotes from both Professor Davis's and Professor Pfeiffer's classes. At one point when a team was prototyping, one of the students was wearing one of their prototypes for their idea to design glasses with visual inputs for hearing impaired users while they are skiing, Professor Davis said to this team:

Professor Davis:	That is a cool idea with the [refers with gestures to glasses prototype student is wearing] to kind of let you know what's coming from behind.
Student 1:	Like flashes [of light] on the sides.
Student 2:	And it's like proximity so the light dims, depending.
Professor Davis:	It's one of those you kind of go, maybe everybody wouldn't mind having one? You've never cut someone off coming from behind you? [sarcastically].
Student 3:	Skiing? Never [sarcastically].
Professor Davis:	Never happens? [laughs]
Student 3:	Especially listening to music when I ski. The snowboarders, no offense, are the absolute worst about cutting people off because, it's like nothing about you, it's just literally how snowboards are built when you turn, you can't see anything behind you. So that's why skiers hate snowboarders cause you just like cut us off.

Later, during the last day the students were working on their project in the seminar class, the same team as in previous example had the following conversation with the other professor in the room, Professor Pfeiffer:

Professor Pfeiffer:	What project are you doing?
Student 1:	We're doing for deaf people, ski goggles that have sensors, so it alerts them to things like objects and obstacles.
Professor Pfeiffer:	Oh, that's cool.
Student 2:	It's kind of like with the car, how you have a blind spot monitoring. It's like that.
Professor Pfeiffer:	Yep. Oh, that's nice. Yeah.
Student 1:	And I feel like that would be useful for even like ... I would use that when say it's hard to hear. So we were thinking, sensors that just like measure relative speed, and alert you if someone's going to like pass you.
Professor Pfeiffer:	Yep. Cool.

This example shows that during the first interaction with Professor Davis, the students were listening to his comments about the idea being useful for other user groups. The scaffolding that

Professor Davis had provided, in the form of pushing them to think about other potential users of the design, was effective enough that they took his ideas enough to heart that they repeated it to their other professor several weeks later.

Explicitly discussed future support and scaffolding

Professor Davis made frequent references to their future experiences at the university and in their careers, relating what they were doing in their current class to future opportunities. For example, during his introduction of the project to the whole class, Professor Davis said "I told you guys from the beginning, this is like a mini shot at senior project, right? This is, we're doing the same thing we do in the beginning of senior project." Here, he explicitly told the students that they were practicing a design project for their future, in this case for senior design. A few minutes later, when explaining to the whole class what they will be doing for the design project, he told the class that they would be prototyping their ideas with simple materials and described how they would use more advanced materials later in their academic careers as they learned more about design:

> This is foam board and glue sticks and, and we've just, we want you to get down to three ideas today. That's the goal is to have a team and have three potential ideas. […] Has anyone ever heard of the company IDEO, IDEO? It's out of the Bay area. Kind of spun off of Stanford, bunch of Stanford people. This is one of the things that they say all the time is just build it, build it, build it. You know on Tuesday, it was really neat [in the prototyping lab where the class was working and two senior design project teams were also working]. […] There was a third quarter senior project team building [their final project prototype with] stainless steel axles and big metal parts, and there was a first quarter senior project team doing a PVC prototype, first full-scale prototype of what they're going to build in the spring. And then all the freshmen working with me kind of surrounding them [working on their prototypes with simpler materials]. So, it's kind of cool to see that we're just going to keep encouraging you to do this [building with more and more advanced materials as you prototype more].

In this example, Professor Davis referenced a design company and their philosophy about prototyping, reinforcing the idea that the students are practicing the same techniques as engineering designers in industry. He then expanded on other experiences the students would have at the university that would help them develop these skills further. In doing so, he explicitly told the students about the scaffolding and supports that were in place throughout their experiences at the university. He laid out to them that in this introductory class, they would have the support of him as the instructor, but eventually this support would be taken away and they would be expected to work more independently on their projects.

Scaffolded engineering content knowledge

Professor Davis used conversations with the teams to introduce or expand on engineering concepts that they will learn about later in their education. In general, he presented the project as a chance to practice design skills, such as problem scoping, brainstorming, teaming, etc. Although he set up the classroom to support the students through the engineering design process, there were few instances in which he directly talked about the design process or how students should move through their design process. One example in which he did directly give support to the students about how to develop their solution occurred during the first day of the design project when students were developing their prototypes:

Student:	So, if we already know which thing [design idea] we're going to do specifically…
Professor Davis:	[interrupting student] No you don't.
Student:	Do you want us to make three still?
Professor Davis:	You don't have to make three prototypes, but I want you thinking about three ideas. So you want… how would you make it, what kind of materials? So you want to, you got enough time today to kind of think about three and basically you still have tomorrow to narrow down to one. And then you'll really start detailing it out and try to do as much as you can.

In this example, Professor Davis told the students that they should still be considering multiple ideas, providing some support to prevent the students from becoming fixated on a single idea early in the design process.

Other times, Professor Davis provided scaffolding for the technical engineering science content, although this content was also rare. He did not expect students to apply complex engineering ideas yet in this introductory project. He clarified this expectation to one team by saying, "Look, you guys, we understand, you haven't had materials science yet. You just, you're going to do more, describe 'I want it soft, but not too soft'." However, when he noticed misconceptions that the students had, he told them further information about the concepts to help overcome these misconceptions before they were further reinforced. For example, earlier this same team wanted to use a gel like material to hold an attachment in place. Professor Davis took some time to explain the properties of the material:

Professor Davis: But I think the jelly, it, it creeps we call it. So, if you put a load on it, it'll never stop moving. It'll just keep going like this [demonstrates with hand].

Student: Got you.

Professor Davis: There's plenty of things that will work. Just say like an elastomer, some kind of elastic. But the jelly is, even plastics, all plastics do that [picks up piece of plastic from table]. If you put a high enough load on this, if you left this here overnight and come in tomorrow the displacement will be higher tomorrow than it was today.

Student: Yeah?

Professor Davis: Plastics creep. If the load was low enough, the creep would be so small you wouldn't even be able to measure it, but if you put a high enough load on this, and you know we set it up in a ring and measure the displacement, when we come back tomorrow, it will have gone further. One of the things when I teach the junior level class, I spend a lot of the time on showing the students what they don't know. Right, because sophomore year you're going to fill the tool belt with lots of knowledge, right? And then we start designing stuff junior year with it, but at the undergraduate level, there's still kind of our basic knowledge only goes so far. We talked about linear springs, right? When we did the spring lab? When you get into nonlinear materials, biological materials, things like that, that's grad school. Like we just don't have the tools, you guys won't have the tools, no undergrads have those tools. And so you just have to keep remembering, here's the fundamental assumptions we made when we learned this theory, you know like PL cubed over 3I was the cantilever beam we did in lab. There's a lot behind that equation. There's many assumptions built into that equation. And so as a designer you go, OK, can I use that for plastic? The answer is kind of. Not always.

In this example, Professor Davis gave the students some information about the topic, while also reminding them that they had a lot more to learn about the topic. He related his explanation to an earlier activity from the class, the spring lab, and pointed them towards future activities that would further their knowledge. This situation required Professor Davis to assess the students' understanding of materials, identify that they had a misconception, and judge how much information to give them to overcome this misconception without taking too far of a tangent from what they were currently working on, demonstrating many of the challenging aspects of effective instructional scaffolding.

Professor Davis used storytelling throughout many of his interactions with his students to build a framework for the students to think within. He used his stories to give students examples of how to think about problems and to provide scaffolding for furthering their ideas. He used his talk and interactions with his students to build on their passions for engineering and to help them understand the discipline of mechanical engineering. He also explicitly discussed their future careers at the university and in industry and connected what they were learning in their introductory course to these future experiences. Professor Davis scaffolded technical content about engineering design if he noticed misconceptions, but usually focused their attention on learning about other things outside of pure technical knowledge, such as teaming and iteration of designs.

4.4.2 Case 2: Professor Pfeiffer

Professor Pfeiffer also teachers the first-year introductory mechanical engineering course. He used his talk to set up a structured classroom environment. Within this rigid structure, he encouraged students to explore broad design ideas independently. During his interactions with students, he primarily listened, interjecting with pointed questions only to push students' ideas further and to remind them of specific components. The following section describes his case with examples from his teacher and interviews.

Used a structured class environment to build the scaffolding

Professor Pfeiffer uses his talk to set up a very defined structure to his class that students could work within to explore their design ideas. This structure fit well with his personality and his views about teacher-student relationships. His view is evidenced by a comment he made in his pre-interview:

> I think, from my experience, there needs to be a tradeoff between being formal and being a friend overall. And so there is, there is I think a good level there where if you are too frank, for example. But that's, that's me personally, and I'm coming from Germany, right? Where we have more formal, I don't let students call me by my first name, whereas I know some other colleagues do, and it might fit their personality better. But my, my thing is I stay as Professor Pfeiffer, but I am available even for personal problems if you want to talk to me, and I help you out.

> I think so the right balance because otherwise I think students confused, "Oh, he's my friend. I don't need to put in the effort. He gives me A anyway." No. You get evaluated based on did you achieve the learning objectives, yes or no? And this is not on the personal relationship you have with me.

His desire to maintain a structured class played out in his teaching. For example, the activity he designed to help students choose their teams was very structured. On the first day of the design project, students came into class with a completed homework assignment that contained at least four potential ides for a design project. Professor Pfeiffer wanted the students to be able to share their ideas with many other students in the class and use these interactions to choose their teammates. To do this sharing, he divided the class into six groups and had each person from one of the groups sit at a different table. He then said to the whole class:

> Everybody gets their own table. OK, so this is how, this is how we will be doing that. It's called "find your design project speed dating." OK, you will have one minute for your elevator pitch. So, I will time it, one minute I will time, everybody moves on. OK, you do that six times. OK? Three person per table go to whatever table you want to start so we will rotate in this manner. OK, when I call time, the three of you who were here, move over here [Professor Pfeiffer walks to other table], those move over here [and so on].

While this activity was going on, he stuck to a rigid timetable and required the students to move onto the next group at the end of each minute. He structured this activity in a very controlled manner that still allowed students to get a lot of practice explaining their design ideas and learning about other design ideas.

One of the structures that Professor Pfeiffer used were references to the engineering design process. He did not use many detailed explanations of the design process, but when interacting with teams of students, he often referenced it as a structure to form their ideas around. For example, Professor Pfeiffer had the following conversation with a team of students who were working on an idea to make a credit card shaped device that a person who is colorblind could use to identify colors:

Student:	Is there a particular point that you would like us to get to? An end goal?
Professor Pfeiffer:	Well, remember the end goal is you have your final prototype and to have your poster done.
Student:	So, work until we get to there?
Professor Pfeiffer:	Correct. Improve and then think about what else can you do. It doesn't mean you have to stick with that one idea. So, if

that does identify color, maybe you can expand it, you know? Can think about: Are there other constraints? Using that, is that really comfortable in my hand? If it's a box like that, do you want to have it more ergonomically shaped? So like I said, you have plenty of time to think, work about it, use the engineering design process, right? This is actually hands on doing it, kind of learning about it, learning about iteration, learning about the requirements, how do you evaluate that design. If you want to go further if you have more time, how would you market the device?

Student: Sounds good.

Professor Pfeiffer: Again, the sky is the limit.

Examples like these in which Professor Pfeiffer made a brief reference to the engineering design process were common. In another example, at the end of the first prototyping day, the following piece of a conversation occurred:

Student: We're back at the beginning again.

Professor Pfeiffer: That's the whole engineering design process works. That's good, yeah.

In these examples, Professor Pfeiffer reminded the students about the engineering design process, especially the iterative nature of the design process, and related it to the particular point they were at in their project. However, although he made short references like these to the engineering design process or two particular aspects of engineering design, such as the importance of iteration, he did not define or support a defined structure to the engineering design process.

Supported independent exploration of ideas

Professor Pfeiffer believes that students should have the freedom to try out ideas and explore engineering design within the structured classroom environment that he set up. This belief was shown, for example, when, at the end of the first day that the students worked on the project, he said to the researcher:

> So, kind of for the first time, [let the students] play around a little bit. They actually got it narrowed down more than I thought already. But that's OK. So, you see it's a more hands-off approach, just let them figure it out by themselves.

He shared this view that they should be exploring their ideas directly with the students several times. For example, he had the following exchange with a student during prototyping on the first day of the design project:

Student:	Are we allowed to attach flame throwers to it?
Professor Pfeiffer:	You can, yeah, whatever, it's completely up to you. Again, think outside the box, right? I mean, come up with crazy ideas and then evaluate and see what's possible, right? So, this is usually how that works. Brainstorming phase, nothing's off the table.

By using his talk to give a solid structure of the class, he allowed students to be able to focus on their ideas and come up with crazy ideas, rather than worry about what they need to do to do well in the class.

Although he was very hands-off in his approach, allowing students to explore their ideas themselves, Professor Pfeiffer often checked in with the teams to hear about their design ideas and answer any questions they had. During these interactions, he primarily listened. If he determined that the team was on track, he would leave without saying anything or interrupting. If he noticed that they needed extra support, he would interject with short questions, as demonstrated in the following example. Professor Pfeiffer stood near the team throughout the following dialogue, listening to their conversation for several minutes before making the short comment in the example. This team was working on an idea to make a swing that would be easier for a child with a disability to operate and were discussing possible ways to attach the rope to the swing.

Student 1:	I have an idea. If you put a second rope connected to the handles, from the swing to the handles, then at every point the handle would be close enough that if you dropped it would still be easily droppable from the swing.
Student 3:	So are you saying like a mini string right here that holds it like that?
Student 1:	Yeah
Student 3:	So as it goes, it goes like that.
Student 1:	It would go with the swing. Because that would have
Student 3:	So then if they dropped it, they'd just have to pull on that little string.
Student 1:	Exactly.

Student 2:	What if we could make use of some crazy knot where we could like, in a small amount of space keep a large amount of rope, but then as you move it would just draw rope from that, you know what I mean?
Student 1:	So we have like a tension system?
Student 2:	So because if you're only using like, if you need a short amount of rope but you still need the full range of motion of the swing, maybe you want to have some way of like keeping a large amount of rope in, you know what I mean?
Student 1:	Yeah.
Student 2:	Cause like if you're using a short rope your swing's not going to move.
Student 3:	Would you like to create that knot? […]
Student 2:	Isn't that, can't you do that? I'm not crazy, that's got to be a thing.
Student 4:	I don't think that's a thing, that's just like an infinity knot.
Student 3:	I love infinity knots, but they're really difficult when you're trying to swing.
Student 1:	I don't know about a knot, but you could make a coil that was like spring loaded so that it would constantly pull on the one end. […]
Professor Pfeiffer:	So keep in mind right, if there's friction, it will slow down the swing.
Student 2:	Right.
Student 4:	That's what we're doing, these are like little friction holders [points to prototype]
Student 3:	That's so they can pull on the rope.
	[…Students argue over who can tie the knot…]
Student 1:	I am not the knot guy. There could be a knot out there, but I wouldn't know about it.
Professor Pfeiffer:	Well, you can go and google it, right?

In this example, Professor Pfeiffer primarily listened while the students hashed out their ideas. He made two small interjections, to point out something else they needed to consider, friction, without telling them directly how to address it, and to give them an option to find out a solution to the argument they were having, to do some research. This type of interaction was very common in

Professor Pfeiffer's class and gave him opportunities to assess where his students were and give support directly to the team if needed.

Although he did not give much direct input to teams as he was listening, he was very diligent about remembering what they were working on, what they were going to try next, and revisiting these ideas with the students. The following two examples demonstrate this pattern. A team was designing a device to make it easier for a user with a single arm amputation to drain pasta. At one point, the team was discussing how to clamp their device to the counter and was unsure about how large their device would be and were concerned about the weight. Part of their conversation was:

Student:	We were also thinking about just a stand. With like a heavy base. But that'd be a lot of weight. I don't know a way to circumvent that.
Professor Pfeiffer:	So yeah, I see you have lots of ideas to build multiple prototypes to say, this is for clamping, this is for base, you know. And then you need to think about the weight, how much should it carry, right? Are we talking a pound or if you're filling a gallon, you know?
Student:	I'd say at least, yeah. A gallon, how much is a gallon? 5 pounds?
Student:	Is 5 pounds good, or heavier? Ten pounds max?
Professor Pfeiffer:	Well, you're designing it, right?
Student:	I'm going to say 10 pounds.
Professor Pfeiffer:	10 pounds?
Student:	Ten pounds is big.
Professor Pfeiffer:	Yes.
Student:	[to teammate] Research how much a typical serving size of pasta is.
Student:	Actually, I'll be right back. I'm going to go fill this [cup they are using in their prototype] with water and see how much that weighs.

During this interaction, Professor Pfeiffer did not directly give the students any ideas. When they asked him a question, he either restated what they had already said or pointed out that they were the designers, not him, leaving the design in the students' hands and maintaining their control of their ideas. Thirteen minutes later, Professor Pfeiffer returned to the team and said:

Professor Pfeiffer:	So how did it work out with the water?
Student:	We didn't get to exactly balance it.
Student:	It wasn't really the weight that was the problem, it was flipping side to side.
Professor Pfeiffer:	So, it was not stable basically?
Student:	Yes.
Professor Pfeiffer:	Ah, OK.
Student:	I guess we're going to, I guess in our final design we're going to design something to lock it.
Professor Pfeiffer:	Yeah, that's a good idea, yeah. See by experimenting around, you get more ideas to improve it.

His process of checking on the students held them accountable for improving their designs and following through on their ideas, without him needing to interfere directly in their design processes. This process allowed the students to maintain their control of the design but kept high expectations of what they should accomplish. Additionally, it gave them several opportunities to ask questions if they needed support from the instructor as the more knowledgeable other.

Adapted his talk to meet the students' needs based on frequent questions to the students

Professor Pfeiffer highly values personalized interactions with his students and adapting his pedagogies to fit their needs. This value was evidenced in his pre-interview when he responded to the question, "What do you think are effective ways that you as a professor can support your students when they struggle during design projects?" saying:

> […] it's regularly meeting with them in person. So we do that in the HVAC senior design and yeah, you need to put in the time and effort as well. So it really depends on the project, on the students. From my experiences you cannot just say "okay we meet each week for an hour" because for some, at the beginning, I just need to meet with them 10 minutes and then later, for example, I need to put in three, four hours with the students. And that, you know, it varies. So you need to be able to adjust to that. You cannot like can it and say "it's always an hour and that has to be enough." If you really are interested in helping the students succeed.

Throughout the design project, Professor Pfeiffer frequently checked in on the students, asked them to share their ideas and based the rest of his interaction on his assessments of their progress. He did not directly tell them any ideas or suggest specific ways for them to move forward. He used prompts and questions to challenge their ideas or provide next steps. As an example, he had the following conversation with a team after they had formed a team and started brainstorming their ideas:

Professor Pfeiffer:	So, what is your idea? Or ideas you want to pursue right now?
Student:	One of the ones that we singled out is a wheelchair mount on a longboard.
Professor Pfeiffer:	Oh, OK.
Student:	So it would allow users to like roll up onto the board then it would lock into place.
Professor Pfeiffer:	Mm-hmm
Student:	And it'd be electric, so they control like acceleration and braking.
Professor Pfeiffer:	OK.
Student:	And then there'd be like quick release buttons on the side to unlock and pull it off.
Professor Pfeiffer:	OK, cool. Yeah well you have the stuff here [to prototype with], right? You can cut the cork, you have little wheels, toothpicks whatever, yeah.
Student:	Absolutely.
Professor Pfeiffer:	OK, good.

In this example, Professor Pfeiffer gave his students opportunities to practice explaining his ideas. He let them know that he was available if they had questions and confirmed that they knew what materials they had available to them but let them continue with their design ideas however they chose.

On the other hand, when Professor Pfeiffer made assessments of the students and determined that they needed more support, he prompted them with questions or further things to consider. For example, while a team was finishing up a prototype, he complimented their work and then suggested:

> So the idea is to come up with a prototype, right? And then evaluate. That's what engineers do. So let's look what we can up, pro and cons, right? Write them down and then think about to improve it, OK? That's the iterative process of your design. Did you address all the customer needs? Yes or no, right? Is it safe? What can be done better? What are some of the challenges we perceive, right? If you keep your first prototype and then you build a second one later you can show the progression,

> right? How you started, this was the first idea but then that was our final idea, and these are the reasons why that final one is better than that first one we did.

In this example, the students had already built one prototype. Professor Pfeiffer provided scaffolding by asking questions to help them think about how to push their ideas further. He did not give direct advice about their prototype or idea but did remind them of things they should be considering and how these considerations fell within the larger scope of the project and engineering. Professor Pfeiffer made very similar comments to this example to all the teams, but at different times based on their progress.

Professor Pfeiffer used his talk to scaffold his students' learning about engineering design in a variety of ways. He used his talk to set up a very structured environment that allowed students to clearly understand what they should be doing when. However, within this structure, he gave his students freedom to explore their ideas and push the limits of their knowledge. He supported this exploration by frequently checking on the students and using his interactions to assess the students' understandings in order to tailor his scaffolding to what each team needed in the moment. During interactions with the students, he did not give direct answers, instead prompting them by repeating their own comments in different ways, asking questions to further their thinking, and prompting them to think about other aspects of the problem.

4.4.3 Case 3: Professor Wilson

Professor Wilson teaches the sophomore level biomedical engineering course that includes the students' first experience with design at the university. He used his talk to provide students with a scaffolded industry practice. He views his role as the introductory professor is to prepare his students directly for their first internship or industry experience, especially with the acronyms and language about biomedical engineering processes that they will need to understand their industry colleagues. The following section describes how these patterns were illustrated in his classroom and interviews.

Structured his class as a scaffolded industry practice

Professor Wilson held the viewpoint that his course should directly prepare his students for an industry experience. He used his talk to set up a classroom model similar to what he has seen in industry. For example, he said to the researcher:

> When I took it [teaching of the course], all I did was I said, “I'm just going to treat this class like I would treat my company or what I would do in industry,” and literally, that's just what I did. I just started treating the students, I said, “I'm going to make this feel like you're project engineers.” That's really the direction the class has taken since I've been teaching it. That's kind of all I do, I just treat it just like out their [in industry], like what I would do if I was at work.

This philosophy is mirrored in how he set up his classroom and how he talked to his students. Overall, he spent some time giving an introduction to the project and telling students the important parts of what they needed to do. He did give the students several guiding prompts but left the project very open-ended, evidenced, for example, when he told the whole class:

> You will have an aim, you will have, you know just something rough that describes the problem. And then you’ll talk about, what will be the deliverable, maybe it’s a process, maybe it’s a product, maybe it’s a service and a process, and you’re going to roughly talk about what you think that’s going to be. […] And then what do you think the impact of your device will have in that market space? What will be the impact? Will it be something that help… you know I talk about what my company’s working on, will it be something that will help move people that are asymptotic in cardiovascular disease into the symptomatic range [like my company’s product does]? Maybe that’s the aim. But you know it’s what you want your product to do in whatever space you are interested in as a team.

After giving this information, he let the students work. He answered questions when students came up to him but did not check on teams or interrupt their work. As he said in his pre-interview, “I like for them to be able to solve it themselves. If they can't, then I will get involved.” There were only three instances in which teams asked questions to Professor Wilson. One of these examples, was the following conversation:

Student:	I just wanted to like get your sort of like opinion on like the scope of these ideas.
Professor Wilson:	Yeah, yeah
Student:	The first one is like a targeted chemotherapy. Because chemotherapy kills a majority of the cells. So this would be like marking the cancer cells and then targeting those specifically.
Professor Wilson:	Yeah
Student:	The second one would be targeted treatment of bacterial [pause], with antibiotics that could mutate at the same rate as the bacteria. The last one would be an early diagnosis and cure for Huntington’s disease.
Professor Wilson:	No, I think those are good.

Student:	Those are pretty…
Professor Wilson:	Yeah, yeah
Student:	Where it's more, some of them are more like conceptual.
Professor Wilson:	Like diagnostics, it's like diagnostics, but you'll talk about how you're going to diagnosis it.
Student:	Right. So these are good scopes?
Professor Wilson:	Yeah, yeah. That's fine
Student:	Thank you so much.

In this example, Professor Wilson listened to the student and gave some validation for the ideas but did not critique them at all or direct the students how to proceed further.

He expected students to do most of the work for the project outside of class. Other than the 50 minutes during the initial class period, the students completed the entirety of the project outside of class time.

Modeled specific language and acronym use

Professor Wilson based the goals of his class and the ways that he used language in his classroom on his experiences in industry. He wants his students to be able to go out into the biomedical engineering workforce and be prepared for success. This goal was demonstrated, for example, when he told the researcher:

> I want them [the students] to be able to go into a medical device company, because what I remember, when I was 18, I went to my first internship; I remember being shocked that I had something to contribute. Because all I had was like freshmen chemistry, freshmen physics, and I remember being shocked, because like the fact that I could balance a reaction was actually valuable. And I remember being shocked. And so, I said I don't want them to go into a company and be shocked that they have something to contribute.

Professor Wilson views a significant role of his talk in the introductory class is to prepare the students to be familiar with the language of the discipline of biomedical engineering so that when they go into internships and other industry experiences they will have the tools to be able to communicate with their colleagues. He stated this aim in his interview with the researcher when asked about important aspects of language in the classroom:

> It's just, I think acronyms. I know that's a joke that they [the students] have but I tell them that's one of the big things in engineering, is we have a lot of them. And

> so, I try to make light of the fact that because, the first couple quizzes I gave, they didn't remember any of them. I mean, so trying to make light of them I said, "I know that I can't go five minutes without using one but these are like…People are going to walk up to you and say, "Oh did you get the FMEA done?" or "Have you done the OQ protocol?" That's just what they're going to say to you. And at some point, this will become second nature. But my job is to be kind of the intro person that makes these biomedical engineering acronyms begin to become second nature. So, I think that's part of it is I think that's the hardest part of, at least, the engineering language part of it.

He uses acronyms a lot with his students and is up front with them about his goals to help them learn the acronyms and that he agrees that there are a lot of acronyms in engineering that they need to learn. In the following example, he brings up several acronyms when talking to the whole class:

Professor Wilson:	The high risk is class 3. And there's a different pathway for that. But remember there were two different pathways. We had generally exempt, we had generally this pathway and we had this key word, do you remember this key word? [writes word on whiteboard] We had that key word that was in there.
Student:	510K
Professor Wilson:	510K, that's exactly right. And then we had, you know we've gone 5 minutes in the class without an acronym, so we have to have one, right? [laughs] So class 3, is what?
Student:	PMA
Professor Wilson:	PMA. OK. Pre-market approval.

In this example, Professor Wilson expected the students to come up with the acronyms for the situation, continuing a standing joke that they do not go five minutes in the class without using an acronym.

In addition to the use of acronyms, one of Professor Wilson's major points of emphasis was on the procedures that an engineer needs to go through to produce their project and support the students to be able to use the language associated with those processes. For example, when he introduced the project, he used an example project [called House Calls Mobiles] from a previous student to walk through some of these steps and processes:

Professor Wilson:	She had a very novel idea. And hopefully, it's useful and not obvious, right? Because then…
Student:	Patent

Professor Wilson: She can get a patent. So, she can do those three things, she can get a patent. And she actually has, she did get a patent, so it did meet those three criteria. And what it is, it allows a physician to do remotely, to have the ability to hear heart sounds and to actually do an inner ear examination at the same time, so it's a combination otoscope/stethoscope. And it's virtual. So this was a team that worked on it. Some of the students are gone. Some students are here [at the university]. [pulls up slide for "Indications for Use"] Why is this important? We talked about this. What is this? Why does the House Calls Mobiles need this?

Student: You need to say to the FDA what your device does and who you tested it on and then how, which age, which type of people would it benefit, you could use it for.

Professor Wilson: Yeah. This is her contract with the FDA. It's stating what the product does. Who it's going to be used on. What its requirements need to be. Maybe where it can't be used and it has all this information here. So, this is her indications of use statement. So that's the first thing the team developed for her, they helped develop that. And the other thing I want you to think about is, we talked about here in class if every person in this space used your tool, how many people would use it, and, is there an estimated cost that goes with it? And you're going to multiply that total number of people that would use your product if every person in that space used it by that estimated cost you're going to come up with the total available market. So, you're going to come up with that that information as well. So, they moved forward and the other things we talked about were [pulls up Regulatory Plan slide] classifications, right? Remember we talked about, well what are the three we talked about? We talked about class 1, 2, and 3. [continues talking about differences between classes]

This example demonstrates an example of the ways that Professor Wilson emphasized the language around the processes of biomedical engineering. He recalled prior knowledge about the language used around patent processes and expanded on this idea to further explain what needs to be done through the process. He posed many questions that students should be thinking about as they develop their design and the documentation around their design.

Supported opportunities to brainstorm "unfeasible" ideas

Professor Wilson views a purpose of the introductory design class as helping students brainstorm ideas about the potential future, even if these ideas are not feasible yet. At the very beginning of his introduction to the project, he told the whole class:

> I don't necessarily want you to think about things that…they don't necessarily have to be feasible. At this point, because you're not going to have to build them, however, what I want you to be able to do it still go through the steps as if they were feasible and be able to develop these stages for the concept review because at one point basically anything that you see that's on the market right now there was a point when people said it was probably impossible to make. Right? Right? And so, I don't want you to keep yourself in the box up saying, "OK, it's got to be, you know, similar to the current digital measurements that are made for temperature or whatever." I want you to think outside the box because at some point, maybe there will be the technology to do the things that you're going to do, and you will already have it at a concept review, you'll be able to move forward. So that's really the game plan.

In this example, Professor Wilson encouraged his students to brainstorm broadly and to consider unfeasible ideas. He pointed to the rapidly changing nature of working on design projects and the need to be forward thinking in order to develop successful designs.

In addition to promoting students to brainstorm unfeasible ideas, Professor Wilson encouraged the students to develop their ideas further and often reminded them of the entrepreneurial potential of their ideas. He said similar things several times in his talk to the whole class, such as with references to the example design project he was using and references to his own company (in earlier examples in this section). Additionally, although he only had a few interactions with teams of students, he continued his support during these interactions. For example, Professor Wilson had the following conversation with a team as they were working:

Student:	We only have, we only have like two of ours's [ideas] right now.
Professor Wilson:	OK
Student:	One of which we already…
Student:	We've already done a bunch of research on this one.
Professor Wilson:	No, I think that's, so definitely kind of start that one too and that'd be good if you've done some research on it already.
Student:	OK
Professor Wilson:	Yeah, so I know that there's, yeah. Ok, so what's this one?

Student: It's a, I found something that just got released called Mitro which is a glue that helps keep tissues together. They've expanded that to help heal muscles for women who have c-sections.

Professor Wilson: Yeah, that's a good one. That is good.

Student: So now you can heal the c-section and they will be able to go to [inaudible] faster.

Professor Wilson: You need to, what's the, have you talked to [name]?

Student: Not yet.

Professor Wilson: Because that's her, her product, I can't think of the name of the product. She's in Africa right now, doing a study, maybe she hasn't left yet, I know she said she was going to Africa. But it's hemorrhaging. So, her performance metric is you know, blood loss during a delivery. But it's a tool. This is something, maybe get her insights on. 'Cause I know I saw some pictures; I spoke in her class last week and I saw some pictures where she was showing some pictures from some of the tests they did at the hospitals. So she'd be a really good person to talk to about this idea. [Students write that down]

Student: [asks question about logistics of the assignment]

Professor Wilson: […] I think that's a good idea. And it's, it's, the thing that's really good about these is hopefully you'll keep them and you'll keep these ideas when you take [other class names]. Because one of the things I'm working with right now, I'm working with real sponsors that are outside and I think I told you that one of the sponsors is back in [place name] and we're developing a novel in vitro feralization tool with some graduate students and so there's positions that we can get to help and I think the beauty of kind of what you saw with senior design [points to slides] and these ideas is they're not academic projects. They're real projects. It's good and it's bad because there's some pressure, it's not just a class now. You know, so it's good and it's bad that they become real.

Student: There's consequences.

Professor Wilson: Yeah, I think it's good and it's bad, but for the most part there's more good than bad that comes from it. Because I think of my senior design project and we just had a project where we had to develop a model to separate natural gas into its first four components and anybody could do that back in the 80s, so it wasn't very real, but, and everybody had the same project in my chemical engineering class. But ours's are, everybody has a different one and they're all like real, so that's why the functional prototype thing that I showed was so important. So this could be a good one. I'd talk to [name]. If it's something that in a couple

> years, you're still, or a year and a half, you're still passionate about, I'd go for it. Ok, good work. Thank you

In this example, Professor Wilson validated their idea and pointed them in the direction of a specific person that he thought could give them more support to develop their ideas. He encouraged them to think about the real-life applications and potential of their ideas.

Professor Wilson used his talk to set up a structure similar to his experiences in industry in which he gave students initial, open-ended instructions and let them work mostly independently. He emphasized specific language used in the biomedical engineering industry, especially acronyms and language around regulatory processes. He supported students' brainstorming of unfeasible ideas and pointed them in directions to further develop their ideas and apply those ideas to the real world.

4.5 Cross Case Synthesis and Discussion

This section synthesizes across the three cases based on the theoretical framework. The patterns that emerged are based on the results of each case and supporting data from the interviews are used to add additional support to these patterns.

4.5.1 Overall approaches to using talk as scaffolding

Each of the professors had different approaches to how they used their talk to scaffold their students during engineering design projects. They all set up a structure to their classroom and guided their students through the design project, although they did so in different ways. For example, although they all set up the project as a team project, when students were actively working on their projects in teams, each professor had a different approach. Professor Pfeiffer's primary strategy was to approach teams, ask students to explain their ideas, listen to their ideas, and ask a few prompting questions. He assessed each team's progress and tailored his prompting questions to where they were in the process to push their thinking forward. His interactions with the students were on topic and did not last any longer than they needed to in order to assess the team and make sure they were on a good track. Professor Davis, on the other hand, had longer interactions that usually involved stories and talked about other "cool" ideas related to their design. He often went on tangents with the students to talk about a host of topics, some closely related, and others not related to the project the students were working on. Professor Wilson took a still different approach and rarely interacted with students as they were working, except in the rare case when students initiated a conversation, in which he followed through with suggestions of how to move forward. Each of these approaches demonstrates a different approach to using talk as scaffolding. Professor Pfeiffer used his talk to scaffold student in a pattern, asking for student ideas, assessing those ideas, following up with prompting questions, checking on students' progress, and repeating, that is very common and has been shown to be effective (van de Pol et al., 2014). Professor Davis was much more casual in his support, often intertwining the support within a story in a less clear manner, but still giving the students support and interacting with them for longer periods of time. These interactions had the advantage of providing students with context around what they were working on and helping them develop relationships with their professor. Additionally, his strategy of using stories to situate design learning agrees with the work of Lloyd (1998) that found that "designing is described as an activity that depends largely on experience, and as storytelling is a way of explaining experience, it seems a particularly apposite means of explaining designing, particularly designing as a primarily social process" (p. 121). Additionally, Professor Davis's support more often reached further than the small design project the students were working on to incorporate scaffolding about their larger career and academic goals and to provide a cognitive apprenticeship experience for the students (Collins et al., 1989). Professor Wilson's approach allowed students to practice working independently, which is what he valued from his industry experience.

4.5.2 Role as a more knowledgeable other

Each of the professors acted as the more knowledge other in their classroom; however, they used different methods to establish themselves as the more knowledgeable other. Professor Wilson was very explicit in that his experience in industry supported his role as the more knowledgeable other. He used phrases referring to his personal experience, such as "I went to my first internship," "that was my experience when I started designing guidewires," and "I talk about what my company's working on." In his interactions with his students and his comments during the interview, he made it clear that his time in industry gave him experience that he wanted to share with his students and that most of his examples and perspective came from his personal experiences. Professor Davis relied on his experiences with a wide range of contexts and through interactions with diverse groups of people. For example, he often told stories based on the experiences of his friends and others he had interacted with. A few of the people he referenced in his stories when he was talking to his students were, “my wife is an occupational therapist, which is kind of like a physical therapist and she does rehabilitation”, “I was at a wedding quite a long time ago. Two managers from Intel getting married”, “my wife’s best friend’s son, from back east”, “I had a guy that I did my PhD with who was actually a Swiss guy”, and “We got to this dive resort in Indonesia […] we’re having dinner with a guy that got nine stiches behind his ear from a triggerfish the day before.” These examples demonstrate the diverse groups of people that Professor Davis interacts with to gain the experience that has made him the more knowledgeable other in the classroom and how he incorporates their experiences in his talk to provide a rich, diverse experience for his students. Professor Pfeiffer, on the other hand, structured his talk to support students acting as more knowledgeable others for each other, as shown in the examples in his case description. During his interactions with students, he said much less than the other professors, instead pointing the students to support each other and prompting them with questions to discuss in their teams. In each of the cases, the professor was the more knowledgeable other (Vygotsky, 1986), but they emphasized different strengths that they had and different things they were more knowledgeable about. These findings indicate that professors emphasize the aspects of design that they value the most. In Professor Pfeiffer’s case this value was in giving the students opportunities for open-ended exploration of their ideas; in Professor Davis’s case this value was in integrating the design project with stories that related to life in general; and in Professor Wilson’s case, this value was in giving the students practice being an engineer in industry. This finding has implications for what is emphasized in design education. It shows evidence that each professor took on a different role and that each student’s experience was not the same, implying that the professor’s values and experience make a difference in how design is portrayed to students.

One of the ways that both Professor Davis and Wilson differentiated themselves as the more knowledgeable other was through their experiences with failure. They both valued the importance of learning from failure. These values are evidenced in their interviews. When asked “What do you think are effective ways that you as the professor can support your students when they struggle during these engineering design projects?”, Professor Davis said:

> [On the first day of my junior level class] the second to last slide is [name], who was a famous graduate from here in aerospace engineering. The guy designed and built, God only knows, 50, 60, 70 airplanes and he’s the designer of [a famous

> spacecraft], [dialog cut which may reveal the identity of the institution]. And he came and talked here, and he said, "If my engineers aren't failing three or four times a year, they're just not trying." And so, I talk a little bit about that and then my last slide is Yoda, and it just says, "The best teacher failure is." So, I try to let them know that, especially in a design space that you know, or by definition, we're doing things that haven't been done before and you're going to fail and it's okay.

In response to the same question, Professor Wilson said:

> I always try to let them [the students] know that the struggle is an important part of being an engineer. I share with them my failures as a design person and I try to tell them that failure is a part of success and that's the hardest part, is when you're their age. […] They're all used to being like Steph Curry at the free throw line making like 95 percent. And I tell every student that it doesn't work like that. You have to think like you're a really good baseball player and if you get 33% you're good, and, and, but it's tough to do that when you're 18 and we get these amazing students that their average GPA is like 4.9 out of four. And so clearly, they've never not got 100% and I think it's hard to go from when you're used to just sitting down and always getting everything right to all of a sudden, "Oh my gosh, it's not working," and it's more than half of the time. I think that's difficult; it has to feel like the world has been turned upside down to you when you're always used to just getting stuff and just, "I get it right every time." So, I think that's what they struggle with. I tried to tell them, I said, "That's what I think we're here for is to teach you, as bad as it sounds, how to fail."

Both of these quotes demonstrate that the professors valued learning from failure and the importance of failure in design. However, none of the professors devoted any appreciable amount of their talk with students about learning from failure. Their ideas about learning from failure may have come up in other parts of the class that were not observed in this study. However, even if learning from failure did come up in other parts of the class, learning from failure during design is very important (Maltese et al., 2018; Petroski, 1992, 2006) and was missing from the professors' talk during the design projects. If students do not get exposure to learning from failure, even if the professor thinks it is important, they will not get the opportunity to learn from their failures.

4.5.3 Three components of scaffolding: contingency, fading, transfer of responsibility

As described in the theoretical framework, there are three major components of scaffolding; contingency: the teacher's support must be adapted to the student's level; fading: the "gradual withdrawal of the scaffolding" (van de Pol et al., 2010, p. 275) through decreasing "the level and/or amount of support" over time; and transfer of responsibility: responsibility for the performance of a task is gradually transferred to the learner" (Sharpe, 2006; van de Pol et al., 2010; Wood et al., 1976)

Contingency

The professors primarily used their talk as contingent scaffolding (Sharpe, 2006; van de Pol et al., 2010), adapting their talk in the moment to fit the needs of their students. This adaptation is demonstrated, for example, in the examples in each case when the professors asked their students questions about their ideas or their progress and then gave a response personalized to where they were in the process. This pattern is further supported by their pre-interviews. All the professors said that they did not plan ahead of time what they were going to say to their students. When asked by the researcher, "How do you plan what you will say during class time? Do you specifically plan for interactions with your students or do you allow them to arise naturally?", Professor Davis said:

> That [allow them to arise naturally]. […] I've been doing it long enough. I've done the same example problems enough and so now I just kind of let it flow and I watch the clock, to make sure, "Okay, this is where I need to get to."

In response to the same question, Professor Pfeiffer said:

> Yes, see that, I think in my head I think more about content. So, for example, so now I need to introduce the ideal gas equation to the students, right? […] because I taught it a couple of times, I know from previous experience, I introduce the application and I already know what I need to emphasize when I introduce it. You know, watch out for this and this, and this is basically how I prepare it. It's more like a bullet point list, maybe, if at all, because based on experience then I basically, so to speak, have it in my mind what I need to talk about.

Professor Wilson's response to the same question was:

> I try to go live TV, it's what I call it. I try to do that as much as possible. I try to maybe put things out there, like I'll show them something, but I won't know exactly what's going to up when they pick it. Like when we talked about medical device recalls and, but we had talked about, so, I think that's the beauty of live TV. I tell them, "Now, we're going to the live TV segment of class." They know what I'm talking about, so I have these things that make it humorous. I say, "We've talked about all these fundamentals, now we're going to pull up a medical device recall." I'll say, I'll let somebody in the class just say, "Okay, pick one and let's pull it up." We'll click on it and I'm seeing it for the first time just like they are. So I said, "Now we're in the live TV segment of class, I don't know what's going to happen." That's what I said.

All three of these quotes demonstrate that the professors value their experience in being able to talk to their students. They anticipate that their students will ask unexpected questions that they will need to use their experience to answer and adapt their teaching to accommodate these needs.

Fading

There were no clear examples of fading of scaffolding observed in any of the cases. This finding is most likely because the study was conducted over a relatively short period of time and did not represent a long enough time period for the professors to need to fade their scaffolding during this time. It is therefore a limitation of this study that we are not able to make conclusions about how the professors may or may not have changed their scaffolding over a longer period of time to incorporate fading.

Transfer of responsibility

The professors used strategies to transfer the responsibility to the students (van de Pol et al., 2010). For example, as evidenced in the example given in the results section when Professor Wilson was talking to a team about their idea related to a new technology to help healing after C-sections, he suggested they go talk to another, more advanced student who was focusing on this topic. In this example, he had already given the students their assignment and the basics on how to do it and was transferring the responsibility to them to continue the work. Another strategy the professors used to transfer responsibility was references to their future work and how they would need to take more and more ownership of their work as they advanced through the design project and through future design projects. This strategy is shown in the examples in the case description for Professor Davis that demonstrate a few of the times he referenced senior design projects or industry experiences. Additionally, the professors encouraged their students to develop unfeasible ideas that they could continue to develop as practicing engineers. This strategy is shown in the examples in Professor Wilson’s and Pfeiffer’s case descriptions. In using this strategy, the professors encouraged the students to think ahead to the future when they would be responsible for coming up with their engineering ideas and carrying them through. This encouragement demonstrates the transfer of responsibility from student to engineer that the students will need to go through in their careers.

4.5.4 Scaffolding specific to design

All the professors took on the important role of guiding their students towards overcoming challenges in design, such as those laid out by Crismond and Adams (2012). For example, the professors supported their students towards grappling with the open-ended nature of the design projects in several ways. They sometimes explicitly told their students that it was challenging and encouraged them to take this relatively low stakes opportunity to practice, such as when Professor Davis told a team "I'm going to leave that one up for you. I told you, the problem with these questions is there's no answers." They used their talk to ask prompting questions to further students' ideas and broaden their ideas about the applications of their ideas. Additionally, they pointed their students to other people and resources that could help support their ideas and, especially in Professor Davis's case, gave diverse examples of people and stories effected by designs. Both Professors Pfeiffer and Davis supported their students towards the practice of representing ideas towards the informed design practice to "use multiple representations to explore and investigate design ideas" (p. 748) by encouraging students to make prototypes, pointing them towards resources to construct their prototype or giving suggestions about how to use materials, and requiring them to make a poster on which they sketched their design ideas. All three professors also encouraged their students to avoid idea fixation, a common challenge for novice designers (Crismond & Adams, 2012; Faas et al., 2014; Sio et al., 2015). For example, Professor Wilson explicitly told the whole class to think about ideas that were not possible yet because they might be possible in 5-10 years when students were working in the biomedical engineering workforce. As his students were sharing their ideas and choosing teammates, Professor Davis encouraged his students to listen to many different ideas before making any decisions. Professor Pfeiffer told his students several times to "think outside the box" such as when a student asked if they could use flame throwers on their design. However, there were other patterns of beginning designers that the professors did as thoroughly address, including problem scoping, testing and troubleshooting, and reflecting on the process.

The professors all spent very little time talking about the overall engineering design process and they did not reinforce a concrete definition of design. None of them gave specific strategies or skills for certain parts of design. They generally had the students try out ideas and engaged them in conversations as they were working. Although this strategy can be effective to support students in the moment with what they need, more structured support for the entire design process could have helped them develop a more holistic understanding that could help them transfer their ideas to other contexts. In order to learn design, students must be exposed to both the knowledge about design and gain experience with the skills needed for design (Christiaans & Venselaar, 2005). The professors in this study gave very little instruction in the knowledge about design. Therefore, even though students gained experience with design, they did not get as rich of a learning experience as they could have if the professors had provided more support for the knowledge about design. This result was probably influenced by their ideas that they all had an open-ended view of design. For example, when asked "What experiences have you had with engineering design, both as the designer and the teacher of design?", Professor Davis said "…the whole definition of design. What do you mean by it because it's such a broad term?" In response to the same question, Professor Pfeiffer said, "So, well, that depends on how you define design, right?" Neither professor gave a clear definition of design nor waited for the researcher to provide a definition before continuing on to list their experiences with design, however, their comments demonstrated that they view design as a broad, open-ended concept. If a goal of an introductory design project like those studied in this research is to learn about the design process and be able to transfer their knowledge to different design projects, the students need more exposure and instruction in the design process. Students need multiple experiences and concepts within the generalizable concept to develop schema about that concept (Vygotsky, 1986).

Each of the professors focused a lot of their talk on the context of the problems, and all of the professors let the students chose the context for their specific project. In the mechanical engineering classes, the students were tasked to design something for people with mobility disabilities, but were not limited beyond this prompt, resulting in projects that ranged from designing kitchen tools for people that could not lift a full pot of water to ski goggles for people with limited hearing to a swing for children with limited leg mobility. In the biomedical engineering class, the students were tasked to design something that helped someone, without further restriction. The professors continued to encourage the students to focus on the context throughout the project with their talk. For example, Professor Davis used his stories to help situate each project within a larger context and encouraged the students to think more about different types of users and different applications of their ideas. The emphasis on context and on allowing the students to decide which context to focus on has implications for students' broader conceptions of engineering because it gave them opportunities to think about how their engineering work could help specific user groups and the world more broadly. It is important for students to see the broader impacts of engineering on the world (Knight et al., 2007). Context is especially important for engaging women and underrepresented minorities in engineering design (Kilgore et al., 2007) and having the professor relate learning to context may help students feel motivated to persist in engineering and see the value of considering context.

None of the professors relied heavily on technical engineering science content, instead focusing on learning objectives focused on skills such as design, teaming, and communication. For example, Professor Pfeiffer made frequent, short references to the iterative nature of design in his interactions with teams, Professor Davis spent a significant amount of his talk during the introduction of the project on teaming, and Professor Wilson emphasized the procedures involved in getting FDA approval and communicating their ideas for that approval. These skills are important for successful engineering design (ABET, 2018; Crawley et al., 2014), and it is significant that the professors emphasized these skills and guided the students through opportunities to practice them as often they are neglected among the learning of the more technical skills (Cross & Clayburn Cross, 1995). Additionally, in many engineering programs it is unclear who is responsible for teaching these skills (Paretti et al., 2011), so it is heartening to see that the professors in this study took on these challenges in the introductory course. However, in addition to learning skills such using design, teaming, and communication in isolation, engineering students also need to learn to apply these skills and integrate them with technical engineering science knowledge. Therefore, it is imperative that students have later design experiences with opportunities to integrate their design skills with technical knowledge so that students do not lose out on the important learning experience of applying their skills to other projects.

4.6 Conclusions

This study used a multiple case study approach to examine how three professors used their talk to scaffold learning during introductory engineering design projects in mechanical and biomedical engineering. Results show that the three professors used their talk to support their role as a guide and mentor to students during their projects although they had different goals with their mentoring. They used their talk to push students' ideas to consider their problems more broadly, encouraged students to brainstorm diverse out-of-the-box ideas, supported teaming, and modeled engineering language. They maintained a focus on non-technical content, including the iterative nature of design, teaming, and communication, but made references to how students would apply this knowledge in future, more technical projects. The professors supported many challenges for novice designers, including supporting prototype development to represent ideas and iterating to improve their ideas, but were not comprehensive in their support of other challenges, especially problem scoping, testing and troubleshooting, and reflecting on the process. These results indicate that professors may struggle to support these areas of design learning and may need additional support to understand their importance and how to scaffold them. Additionally, although two of the three professors explained their view of the importance of learning from failure, they did not use their talk during the design projects to directly support their students learning from their failures, indicating that professors' classroom practices do not directly mirror their learning values. The results of this study also support the importance of having multiple different professors to gain diverse experiences with design, the importance of multiple, follow-up design experiences to apply introductory design skills, and further development of support to understand the design process more holistically. Future work should look at connections between different types of support in the classroom and student learning outcomes. Additionally, future work could focus on the follow-up of the learning in introductory design projects and how it relates to future classes and design projects.

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5. ANALYSIS ACROSS ALL THREE STUDIES

5.1 Comparison across Studies

Each of the studies in this dissertation examined data from across different contexts and aspects of teachers' and professors' talk to address the research question: *How do instructors (teachers and professors) use talk interactions to scaffold students in engineering design?* Although the contexts were different, there are common themes across the three studies that can be capitalized on to address the research question. These themes are examined in this chapter.

5.1.1 Adapted their support using questions

Each of the teachers and professors asked many different types of questions throughout their teaching to adapt their support to meet the needs of the students. These questions were especially prevalent during times when students were working with their teams and the instructor approached the team to talk about their ideas. Teacher talk during teacher-team interactions sometimes consisted entirely of questions. Figure 5-1 displays a summary of the different types of questions that the instructors asked and examples of some of the ways they asked the questions. There were examples like these throughout the studies, these are just a few examples.

Type of question	Examples of Questions
Reminding of problem	**Mr. Evans:** "If corn plants reproduce asexually, if corn plants did not reproduce sexually, would our GMO farmers and non-GMO farmers have a problem?" **Mr. Reed:** "What was the problem that James Randolf [the fictitious client] wanted you to be able to solve?"
Remind of science and mathematics content and earlier experiments	**Ms. Stone:** "Check your data. Did you remember when we did the ice cube melt [experiment]?", "Did it [the material] work well in our lab?" **Ms. Allen:** "How does light behave when it hits a convex lens?" **Ms. Lane:** "How does the light go through the flat lens? […] Does it change at all? Does it have any refractions?" **Mr. Smith:** "What did you do in here [this unit]? Did you do anything with DNA?", "What is pollen? How does it transfer? Through what medium?" **Professor Davis:** "We talked about linear springs, right? When we did the spring lab?"

Figure 5-1. Examples of types of questions asked, all teachers

Figure 5-1 continued

Asking about design ideas	**Mr. Smith**: "OK, so what's your solution?" **Mr. Parker**: "May I ask what's going to happen?" **Professor Pfeiffer**: "What project are you doing?", "So, what is your idea? Or ideas you want to pursue right now?" **Professor Wilson**: "So what's this one [idea]?"
Asking to justify ideas	**Ms. Stone:** "Why'd you pick the copper for the bottom?" **Ms. Lane:** "How did you choose this solution? What did you do?" **Mr. Reed:** "If you were working for me and I was the client, I don't know what you mean by best, what do you mean by best? Gives the best results? […] Why? How do you know? […] How do you know?" **Mr. Parker:** "Can you justify why?"
Pose questions to think about as a designer	**Mr. Reed:** "What are some of your constraints?" **Professor Davis:** "And so as a designer you go, OK, can I use that [material property concept] for plastic?" **Professor Pfeiffer:** "Are there other constraints? Using that, is that really comfortable in my hand? If it's a box like that, do you want to have it more ergonomically shaped?", "If you want to go further if you have more time, how would you market the device?", "Did you address all the customer needs? Yes or no, right? Is it safe? What can be done better? What are some of the challenges we perceive, right?" **Professor Wilson:** "What do you think the impact of your device will have in that market space? What will be the impact?", "How many people would use it, and, is there an estimated cost that goes with it?"
Connecting to lives	**Mr. Reed:** "What would you say? Ryan, corn farmers around here usually have how many, on average, usually have how many acres?" **Professor Davis: "**It's one of those you kind of go, maybe everybody wouldn't mind having one?"
Check on progress	**Mr. Parker:** "How's it coming along over here?" **Ms. Allen:** "How're you guys doing?" **Professor Pfeiffer:** "So how did it work out with the water?"
Specific language	**Professor Wilson:** "Do you remember this key word?"

As Figure 5-1 **Error! Reference source not found.**and the examples throughout all three studies show, different teachers asked different types of questions. The numbers of each type of question that the teachers and professors asked were not equally represented across the contexts.

For example, the professors did more *pose questions to think about as a designer*. These questions prompted students to think about components of their designs in ways that are similar to how engineers think. They also prompted the students to expand their design ideas. Other examples of questions to promote practices of informed designers included questions about *reminding of the problem*, which supported problem scoping, and *asking about design ideas,* which supported communication of the students' design ideas. These questions provide examples of the types of questions that professors and pre-college teachers can ask to prompt student thinking to be more like informed engineering designers.

Although the middle school teachers did not have as much engineering technical knowledge as the professors to base their questions on, they still asked high level questions framed to promote student thinking and learning. These types of questions are important for engineering, but also for learning in many different subjects, including science, with which the middle school teachers were more familiar and comfortable. The strategies that the middle school teachers used included *asking their students to justify their ideas* and *reminding students of the mathematics and science content*. Within these strategies, teachers asked questions within the context of engineering that were not specific to engineering design, which may explain why these science teachers in their first engineering teaching experience were more comfortable asking them. These questions also promoted informed designing in their students due to the need for students to answer the questions with evidence, which may be empirical or come from their mathematics and/or science content. Additionally, the middle school teachers asked more open-ended questions than the professors, which better support students in argumentation and providing evidence for their ideas, elicit student thinking, and encourage reflection (McNeill & Pimentel, 2010; Ong et al., 2016; Scott, 1998; van Zee et al., 2001; van Zee & Minstrell, 1997).

5.1.2 Used their talk to integrate other math/science/technical content—but mostly had students focus on aspects of design (like justifying their ideas, teaming, etc.)

The teachers and professors sometimes discussed the technical science, mathematics, and engineering science content with the students. However, they spent the vast majority of their talk supporting engineering design learning objectives, such as teaming, engineering skills, and design ideas. When they did bring up mathematics or science content, it was usually done so in the context of the problem or as a tool to justify their design ideas. This finding is interesting for several reasons. First, it demonstrates a focus on engineering design content that is often lost in favor of focusing on more concrete, traditional learning objectives that are easier to measure (Cross & Clayburn Cross, 1995). Additionally, bringing up content knowledge in the context of the engineering problem is an important skill for students to learn to become informed designers and well as to see the importance of engineering within their lives and the other disciplines they are learning about (Crawley et al., 2014; Crismond & Adams, 2012).

However, not all of the teachers used their talk to support these ideas in the same ways. For example, the middle school teachers asked their students to justify their ideas much more often and deeply than the undergraduate professors did. By asking their students to justify their ideas, the teachers prompted their students to think about their decisions more deeply, incorporate ideas from multiple aspects of the problem, and work with their teammates to utilize diverse viewpoints (Keong et al., 2016; McNeill & Pimentel, 2010; Ong et al., 2016). The undergraduate professors may have prompted higher levels of thinking and engineering design in their students if they had asked their students to justify their ideas more consistently and more thoroughly. There were also several things that all the teachers could have improved on to better support their students' learning. For example, none of the teachers or professors spent a significant amount of their talk on supporting students' reflections on their ideas or the design process. Reflecting on the process is important for many reasons, including modeling the practices of informed designers, understanding the process in order to optimize it to produce a better solution, and developing an understanding of the process in a way that allows for transfer to new contexts (Christiaans & Venselaar, 2005; Crismond & Adams, 2012; Schön, 1983).

5.1.3 Differences in levels of support across education levels

A significant difference between the approaches to how the middle school teachers and the undergraduate professors used their talk was in the levels of support they gave to students. The middle school teachers more often gave direct support to their students. For example, Mr. Evans (Study 1) was very explicit in his talk to the whole class about topics such as the design process and the connections between the design process and the activities the students were doing. On the other hand, the professors had the approach of giving their students the basics of the activities and primarily let them work. Although it makes sense that the middle school teachers give more support to their students than the undergraduate professors because their students are much younger, less mature, and less experienced students, by not framing their lessons more explicitly (like Mr. Evans did), they might have made it more difficult for their students to make connections across the different concepts in the classroom, such as understanding the overall design process and understanding the connections between the class activities and the design process.

The teachers in Study 2 often gave their students direct feedback or ideas about how to move their designs forward (described in the design ideas section). However, the professors rarely gave their students critiques or direct ideas. For example, Professor Davis usually made indirect critique using stories and Professor Pfeiffer most often restated what the students had said or gave follow-up questions when he noticed struggle. The high levels of support the middle school teachers used to support students' design ideas might have taken away opportunities for students to learn from the struggle with their ideas and through following through with testing and iteration of their ideas. Using strategies more similar to the undergraduate professors, may have given their students more opportunities to explore their own ideas.

5.1.4 How they supported students' design strategies

The teachers and professors used their talk in a variety of ways to support students' design strategies. Figure 5-2 presents the design strategies identified by Crismond and Adams (2012) and gives examples of ways that the teachers and professors used their talk to address each of the strategies. There were additional ways that they addressed these strategies. Each strategy was not represented by equal amounts of time or examples. However, this figure provides a summary of different ways that teacher talk can be used to support students learning to become more informed designers. In Figure 5-2, each of the references in parenthesis at the end of the example are hyperlinked to the relevant quote or section earlier in this document for ease of finding the examples.

Design Strategy	Specific examples of how teachers and professors used their talk to support students' design strategy
Understand the Challenge	• Mr. Evans often framed his talk around the client's problem, reminded the students of the design problem at the start of each class period, made references to activities they were working on, and explained why they were relevant to the engineering design problem (described in section Engineering talk reiterated client's problem.)
Build Knowledge	• Study 2 teachers used many references to their prior work on the science and mathematics focused lessons and often encouraged their students to check their notebooks to use data to support their ideas (described in sections 3.4.6 and Reference engineering notebooks.) • Professor Pfeiffer encouraged students to do research about a component of their potential solution (described on p. 148)
Generate ideas	• Study 3 professors used their talk in a variety of ways to encourage out-of-the-box thinking (described on p. 165) • Professor Davis told his students to consider multiple ideas before settling on one (demonstrated by quote on p. 142)
Represent Ideas	• Teachers often asked students to explain their ideas, encouraging them to represent their ideas as words (described, for example, in sections Teacher engineering talk incorporated and expanded of student inputs and ideas., Prompts to elicit student ideas., and Adapted his talk to meet the students' needs based on frequent questions to the students) • Professors encouraged their students to make prototypes from simple materials to represent their ideas (such as the examples on p. 151 & 158)
Weigh options & Make decisions	• Mr. Smith discussed tradeoffs with some teams (described in section Discuss Tradeoffs.) • Study 2 teachers often told the students directly that they needed to make decisions (described in section Prompt student decisions.)
Conduct experiments	• Professor Pfeiffer told students to keep their prototypes and do tests to show how their prototypes improve (such as the quote on p. 151) • Mr. Evans encouraged his students to conduct tests of their prototype and record them clearly in their engineering notebooks (such as the quote on p. 52)
Troubleshoot	• Ms. Lane and Ms. Allen helped their students walk through their designs to test for specific areas of the laser security system that were not working as expected (such as in the quote on p. 87) • Professor Pfeiffer posed questions to his students about further criteria and constraints they should think about after they have their initial prototype build (such as in the quote on p. 149)

Figure 5-2. Examples of how teachers and professors used their talk to provide support for informed design practices.

Figure 5.2 continued

Revise/Iterate	• Mr. Evans used his talk to model the iterative nature of design (described in section Engineering talk integrated engineering both systematically and opportunistically throughout the unit.) • Ms. Lane reminded her students that they would need to do a redesign to improve their design (quote on p. 94)
Reflect on process	• Study 2 teachers made frequent references to the students' engineering notebooks (described in section Reference engineering notebooks.) • Professor Wilson asked students to think about different regulatory processes and why they were important to their design (such as in quote on p. 156)

5.2 Implications for Teaching

The findings of the three studies in this dissertation point to several key implications for teaching engineering design across education levels. This section describes these implications.

5.2.1 Teachers should expect high-level conversations with their students

The teachers in all three studies had high level, authentically engineering conversations with their students, across students in 6^{th}, 7^{th}, 8^{th} grade and first- and second-year undergraduate students. These conversations demonstrate the high level of expectations teachers should have for their students at all levels of engineering education. Teachers should continue to push their students to have high level conversations with their students at all grade levels to continually improve the conversations they have with their students.

Although some of the talk strategies that the teachers use involve changes in many areas of pedagogies, many of the strategies used by the teachers in these three studies represent strategies that are relatively easy to incorporate into teaching. For example, Mr. Evans (Study 1) framed his lessons around the design project and using his talk to integrate the different subjects. The different levels of support of design ideas (Study 2) represent a structure for teachers to frame their interactions with teams of students. Professor Pfeiffer (Study 3) asked many questions to prompt his students to push their ideas further. Questions similar to these can be used at any grade level to push students' ideas further without telling them how to design their solutions.

5.2.2 Aspects of engineering education are underemphasized

There were several areas of engineering education that were underemphasized in the teachers' and professors' talk. These include ethics, learning from failure, making connections to life outside the classroom, the overall design process, and tradeoffs, all of which are important components of engineering education (Barakat, 2011; Brophy et al., 2008; Goldstein, 2018; Hess et al., 2017; Moore, Glancy, et al., 2014; NAE & NRC, 2009; NAE, 2004; National Society of Professional Engineers, 2007; Pantoya et al., 2015). Although each of the cases and teacher examples in these three studies were limited in scope and therefore did not encompass everything that the teachers said related to these topics over the entirety of their interactions with their students, the fact that they were mostly absent from any of the teachers' talk points to the high possibility that they are rarely discussed in classrooms. Teachers and professors need to use their talk to support all aspects of engineering learning, including ethics, learning from failure, making connections to life outside the classroom, the overall design process, and tradeoffs.

Learning from failure was largely absent from any of the teachers' talk even though it is an important aspect of engineering education and engineering design learning. With the exception of a very short conversation between Mr. Smith and a team, none of the teachers talked about learning from failure. Even though the professors in Study 3 valued learning from failure, as evidenced from the quotes in their pre-interviews, and thought it was a very important thing for their students to learn, they did not use their talk to support learning from failure. This pattern could be an indication that they did not think it was important to have multiple references to learning from failure, or it could be an indication that they did not know how to talk about failure with their students. There are many ways that teachers can be more explicit about helping students develop their skills to learn from failure. For example, Maltese et al. (2018) studied over 100 experienced maker educators to identify strategies they used to support learning from failure with their students. They found that the educators viewed failure as "a foundational concept inherent in the making process" (p. 123) and used strategies to celebrate and value failure. These shared practices included minimizing the strong emotional response to normalize failure through explanations about how iteration is an integral part of design, resisting the urge to step in by suggesting that students seek help from peers first and keeping teacher hands off the project, and use "questions that can guide youth to find their own set of possible solutions" (p. 123). In addition to the challenge of incorporating strategies like these into teaching practices, there are other challenges to overcome regarding failure in the classroom. For example, Lottero-Perdue and Parry (2017) found that many elementary teachers who teach engineering for the first time have negative connotations about failure and often equate failure with mistakes in their interactions with their students. They found that even teachers who externally portray a growth mindset for their students avoid failure for themselves and their students. These findings along with what was seen in the three studies here suggest that teachers can benefit from learning about what failure means in an engineering context and that there needs to be a cultural shift to improve the connotations of the words and ideas around failure.

Another aspect of engineering design learning that was largely absent from the teachers' talk was ethics. Engineering ethics education is varied across contexts and disciplines, and there is limited consensus on best practices for teaching engineering ethics. However, in a systematic literature review of engineering ethics interventions, Hess and Fore (2018) found that the most common pedagogical strategies included "reviewing codes of ethics or standards, such as the National Society of Professional Engineers' (NSPE) code of ethics,… engaging with ethical case studies,…discussing ethical issues in class or out of class amongst their peers,…individually writing a paper of any length on an ethical topic or issue, …[and] reviewing and applying an ethical decision-making or reasoning process" (p. 566). Additionally, this review highlighted several innovative and exemplary pedagogies for teaching engineering ethics, such as "real-world work, community engagement, discussion/debate, mentoring, and a team project" (p. 569) and developing an ethical decision-making model to give students support and application of ethical decision making. Although much of this research was conducted in different contexts than the studies in this dissertation, strategies like these can be incorporated into engineering design projects to support students' application of ethical decision making and ethics understanding in the specific contexts of their projects. Although there has been less research around engineering ethics education with younger students, Sadler et al. (2006) studied the beliefs and practices of middle school science teachers, like those in studies 1 and 2, which has implications for how engineering ethics is taught to middle school students. For example, Sadler et al. (2006) found that life science teachers included more ethics instruction and examples in their teaching in part because they had an easier time seeing the ethical connections with their subject matter than physical science teachers. This suggests that improving pedagogies for engineering ethics instruction starts with supporting teachers, like those in these studies, in their understanding of the importance of engineering ethics and the connections between engineering ethics and its importance for engineering design.

A third aspect of engineering education that was underemphasized in the teachers' talk in all three studies was the overall design process. Although most of the teachers made references to pieces of the design process and sometimes reminded students of the aspects of the design process, such as where they currently were in the process, they rarely and superficially talked about the overall engineering design process. One possible reason for this, especially with the middle school teachers in studies 1 and 2, was that the teachers themselves might not have a complete conceptualization of the engineering design process and did not have the confidence or knowledge to effectively discuss it with their students. This is evidenced, for example, by prior studies that have shown that after their first professional development and teaching experiences with engineering design, teachers are more likely to have general, nonspecific ideas about the engineering design process and to see engineering design as a linear process with a limited number of steps (Mesutoglu & Balan, 2020; Meyer, 2018). Another reason that the teachers and professors may have placed less emphasis on the overall design process was the ambiguous nature of design. This is especially true for the undergraduate professors who indicated in their pre-interviews that they think the word design is very broad and has different meanings based on context and use. However, there are many strategies that teachers and professors can use to support their students' holistic understandings of engineering design, while maintaining broad ideas about design. Many of these strategies are in line with the those suggested by Crismond and Adams (2012) to help students move from beginning to informed designers. For example, Crismond and Adams (2012) suggest that teachers use strategies including "Use words, gestures, artifacts to scaffold visualizing solutions,… give instruction and scaffolding for project management & design steps, [and] encourage taking risks, learning while iterating, and reflecting on how the design problem is framed" (p. 748-749). However, often engineering design strategies are targeted for specific stages of the engineering design project, rather than the overarching design process. Therefore, better understandings and research of how to support students' holistic understandings of engineering design are needed.

5.2.3 Teachers need more and ongoing support

All the teachers in these three studies made great efforts to effectively teach engineering. This effort is especially commendable for the middle school teachers, all of whom had never taught engineering before and none of whom had backgrounds in engineering. They used their talk effectively in many different ways; however, they need more and continuous support in order to improve and to more effectively teach engineering design. Many other studies have shown the benefits of ongoing professional development and support (Diefes-Dux, 2014; Duncan et al., 2011; Mesutoglu & Baran, 2020; Meyer, 2018; Soysal, 2018). With further support, it is exciting to see what teachers can accomplish given the already high levels of engineering teaching that they are doing. In order to improve engineering design teaching, professional development programs should focus on ways to engage students in conversations about other aspects of design and engineering, ways to talk about the aspects of engineering education that are underemphasized (described in the previous section), and help teachers develop further engineering knowledge so they can have the confidence and ability to push their students' ideas even further. Additionally, resources for teachers should work to provide more access to supports to engage students and teachers in meaningful engineering conversations, with special emphasis on the aspects of engineering that are underemphasized.

5.2.4 No single approach is perfect, students need multiple experiences with multiple teachers

Each of the teachers emphasized different components of engineering design and had different strengths in how they used their talk to support students. For example, Mr. Evans (Study 1) used his talk to frame his lessons around the engineering design problem and frequently reminded students about why they were working on the activities that they were doing each day. Mr. Smith (Study 2) was the only teacher to discuss tradeoffs with his students and Mr. Reed (Study 2) spent more talk than the other teachers connecting the engineering design project to the students' lives outside the classroom. Professor Pfeiffer (Study 3) posed many questions to prompt students to think more deeply about their designs (such as the examples in Figure 5-1). Each of these talk strategies are important for a complete engineering education. However, if the students only had exposure to one of these teachers, they did not get the benefits from the other teachers' styles and strengths. Therefore, the studies in this dissertation supports evidence from previous research that students need multiple engineering design experiences in multiple contexts in order to gain a holistic and thorough understanding of engineering design and to identify as potential future engineers (Brophy, et al., 2008; Major & Kirn, 2017; Moore, et al., 2015; Moore, Glancy, et al., 2014; NAE & NRC, 2012). It builds on this research to suggest that these experiences should come with support from multiple teachers. Additionally, as was most apparent in Professor Davis's talk (Study 3), the teachers and professors made references to future experiences in engineering design learning. It is therefore essential that introductory design experiences, such as those studied in this dissertation, are followed up with future design experiences later in middle school, in high school, and in sophomore, junior, and senior level courses (ABET, 2018; Atman, et al., 2007; Froyd, 2012; NGSS Lead States, 2013). These follow-up experiences not only give students opportunities to transfer their knowledge from the introductory design projects to new contexts and problems, but also help them apply their technical content knowledge in different ways that will make them more effective engineering designers and help them understand engineering design more broadly and thoroughly.

5.3 Future Work

Future work should examine connections between teacher talk and student learning, such as how the different levels of support outlined in Study 2 frame students' ideas and learning and how the different strategies used by the professors in Study 3 influence student learning. Additionally, future work could examine connections between teacher talk and students' attitudes, identifies, and perceptions towards engineering, and take into account the student perspective on teacher talk. Further study should focus on how teacher engineering talk aligns with other pedagogical strategies. This work should be conducted in single grade bands and across different levels. Further work should examine changes in teacher talk after further professional development and with more experience teaching engineering. This dissertation focused on two grade bands, middle school and introductory undergraduate. Future work should examine other educational levels to further examine how teachers can adapt their talk to fit the needs of their students and how these needs develop over time.

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