Developing knowledge in engineering science courses: Sense-making and epistemologies in undergraduate mechanical engineering homework sessions

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Abstract

Constructing and applying conceptual knowledge about physical systems is a core activity of practicing mechanical engineers. Yet, studies have shown a surprising proportion of graduating engineering students respond to conceptual questions by recalling fragmented facts and equations; they struggle to reason systematically about the causal mechanisms that drive a phenomenon. One activity where students are expected to develop conceptual engineering knowledge in engineering science courses is during the completion of assigned homework problems. This dissertation examined six undergraduate engineering science homework sessions to identify sense-making conversations that may have lead to conceptual knowledge construction. These episodes of sense-making – or in some cases, only bids for sense-making – were analyzed to understand student shifts from *task production* to *knowledge construction*. Participants were also interviewed about homework sessions and other assigned tasks in engineering courses to explore their *epistemologies*. The interviews showed specifically what students believe counts as knowledge in engineering, how they believe they best develop engineering knowledge, and what pedagogical choices by the instructor students notice as productive for their development of knowledge. Findings have implications for the design of engineering science tasks and future research initiatives about conceptual knowledge building during homework sessions.

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1.1 Introduction

Engineering education research is a rapidly growing field, due in part to the importance of engineering competency to so many sectors of society. With the ever increasing pace of technological development, and its ties to success in world economies and global affairs, educating students for careers in engineering has become an omnipresent national conversation. There are many important things to study in engineering education such as how people learn to design, skill with hardware, ethics, doing engineering in global contexts, teamwork, communication, and diversity. The open questions I seek to explore in this thesis are how to enable all engineering students at the college level to access opportunities for deep conceptual knowledge development in the engineering sciences. Research has already shown that even students who graduate with good grades may not be reasoning systematically or mechanistically about designed and natural systems that are important in different domains of engineering (Streveler, Litzinger, Miller, & Steif, 2008). This dissertation presents fundamental qualitative research in examining the dynamics of homework sessions and students' perceptions of those homework sessions. Specifically, I investigate how students discuss and develop conceptual knowledge in these sessions and the ways students believe they develop knowledge in engineering courses. This work is examining an activity – homework - that is a significant piece of students' experiences but has not been studied in engineering education literature. My reporting on what I see at a very detailed level is hopefully the first step in establishing this line of research and seeding future studies on interventions and the development of different types of homework assignments.

1.1.1 Motivation and Inspiration

The inspiration from this thesis came from two sources: personal experience as an engineering student and courses developed at the Center for Engineering Education and Outreach. As an undergraduate engineering student, I did everything a "good" student should. I went to class everyday, attended optional recitations, went to office hours, and did every problem set. I worked with friends and classmates on all assigned work like faculty told us to during orientation and in classes. Yet, I had this gut feeling I didn't understand everything, and was frustrated like Michael, the "marginalized sense-maker" in Danielak, Elby, and Gupta's (2014) ethnographic study. One of the reasons I went to graduate school was to understand why I had that gut feeling, and to ask how other students could be enabled to build deeper understanding in their core engineering courses. I entered graduate school with a guess the answer might be project-based learning. Those kinds of assignments are where I found success during my undergraduate years.

At the beginning of my doctoral work there was a meeting at the Center for Engineering Education and Outreach about the first year robotics course taught by Ethan Danahy. In the meeting we agreed there was a certain "magic" this course had that inspired students to go above and beyond the requirements of the course and push their technical knowledge to make a project work. I began to investigate this course wondering how the engagement in learning that students demonstrated in this course could be translated to other engineering courses. We decided to examine different out-of-class tasks in different courses to understand how students were learning outside the classroom. In a preliminary proposal examining research on the learning and teaching of feedback control systems, it was clear homework was understudied.

During an independent study with David Hammer, I explored work in science education research to try and characterize this "magic" in the context of the scholarly literature. I started to find answers in the work of Engle and Conant (2002). In their 2002 study of productive disciplinary engagement, they describe elementary school students highly engaged in sophisticated biology thinking due to their pursuit to classify an orca as a dolphin or a whale. I wondered where we could find that kind of intellectual engagement in undergraduate engineering.

1.1.2 Evolution of the Three Studies

The evolution of the three studies of this dissertation followed an interesting trajectory as each study informed the next step in data collection. The original course of study, based on the proposal that arose from that CEEO meeting, was to examine three different types of tasks assigned to students in a control systems course: problem sets, laboratory exercises, and design problems. The first pilot study took place in the spring semester of 2015. Both problem set (out of class) and laboratory (in class) data were collected in two different sections of a third-year control systems course taught by two professors with very different teaching styles. The first analysis of the data examined primarily the laboratory sessions (Swenson, Danahy, & Messner, 2015) and found students primarily discussed the procedure of the lab. Yet, if a professor or teaching assistant was present there were more discussions of conceptual knowledge.

A second pass of the data focused on a single homework session with three students (Swenson & Wendell, 2016). After analyzing this *in situ* video data, I wanted to understand how the participants themselves had perceived and experienced the homework session. In the spring of 2016 we interviewed the three participants a year

after the homework session. Preliminary analysis of the interview data set indicated that when combined with the *in situ* video data, it would help us to better characterize students' overall approach to homework.

One initial finding from the interviews was that two of the three students independently cited a class of problems given by a certain professor as the best type of problem to help them learn. They called these 'Professor Harrington problems,' after the name of the Professor Harrington, and described them as engineering science problems set in a real life scenario that required students to make assumptions before determining any engineering quantities. This finding that students were aware of a special class of problems led us to investigate how students approached this problem type in comparison to others. The study was changed to focus on different types of out of class tasks: problem set problems, Professor Harrington problems, and open-ended design challenges like those found in robotics courses.

During data collection in Professor Harrington's fluid mechanics course, I learned that he does not put these open-ended problems in homework sets but instead on in-class quizzes and tests, during which students do not interact with each other. Thus, it proved difficult to record discourse data while students were doing these problems in real time. Despite not being able to capture this specific problem type, I decided to go forward and capture students working on assigned homework problems. Three teams were recorded doing their homework with one team showing possible instances of disciplinary sense-making. This data was reviewed and preliminary findings can be found in a paper given at the American Society of Engineering Education conference (Swenson & Wendell, 2017).

After a preliminary analysis of video data collected of control systems homework sessions and fluid mechanics homework sessions, as well as the first set of interviews, I decided to focus the study only on engineering science homework problems, rather than also including robotics design projects in the scope of the dissertation. While the interviews with students were initially gathered only to triangulate our analysis of homework sessions, analysis showed students had strong and explicit opinions about which pedagogies aided their learning and what types of learning experiences had the most value. These ideas needed further analysis and seemed important to include as a bigger portion of this dissertation. I now include a whole chapter focusing on these interviews. The second set of interviews, with participants from the recorded fluid mechanics homework sessions, was gathered in the spring of 2017.

1.2 Background

Constructing and applying conceptual knowledge about physical systems is a core activity of practicing mechanical engineers. Accordingly, most undergraduate education programs in mechanical engineering are organized by domains of conceptual knowledge, such as fluid and thermal systems, statics and dynamics, and the mechanics of materials. However, despite coursework being organized by conceptual knowledge domains, a surprising proportion of graduating engineering students respond to conceptual questions by recalling facts and equations; they struggle to reason systematically about the causal mechanisms that drive a phenomenon (Streveler, et al., 2008). Much of the prior work has documented these problematic learning outcomes (Baillie, Goodhew, & Skryabina, 2006), but more research is needed to shed light on the sources of these problems, especially in engineering science courses.

To earn an undergraduate degree from an accredited engineering program, a student must complete one and a half years of engineering topics (48 semester hours) (ABET, 2017). This time is split between engineering design courses and engineering science courses that cover a number of specific domains of knowledge. In the undergraduate program that is the context of this dissertation, mechanical engineering students are required to successfully complete thermodynamics and heat transfer, fluid mechanics, statics and dynamics, circuits and control systems, and mechanics of materials. Overall, they must take at least 10 courses in math and natural sciences and at least 14 engineering courses. Out of these courses, three are required engineering design courses, and 10 are required engineering science courses in the domains mentioned above. Despite initiatives toward curriculum reform, engineering science courses still typically have a lecture-based pedagogy (Kober, 2015). Lectures are usually followed by regularly assigned problem sets that apply the content of the last few lectures and are expected to be completed by students outside of class time. Problem sets are usually comprised of problems from the course textbook or written by the professor. Typically, the problems require mathematical modeling but may also include using software to produce graphs or simulations. Although length varies by instructor, a problem set typically takes several hours of work (and in the U.S., a 3-credit hour college course assumes 6 hours per week of out-of-class effort). Despite the frequency of this type of assignment and the substantial number of hours these assignments take in a typical undergraduate engineering course load, there has been little research into how students approach and learn from these problem sets. In this dissertation, I aim to begin to understand how students work through problem sets, when and how students use and

develop conceptual knowledge and reasoning skills during problem set sessions, and how episodes of sense-making are triggered. To answer these questions we draw upon work in science education about explanations and arguments for sense-making (Engle & Conant, 2002; Berland & Reiser, 2009) and personal epistemologies (Lising & Elby, 2005; Elby & Hammer, 2001; Hammer & Elby, 2002, 2003; Hammer, 1994).

Ethnographic and narrative accounts of engineers in the workplace tend to claim that the primary task of professional engineering is solving design problems (Bucciarelli, 1994; Cross & Cross, 1998). These narratives have been used to justify a focus on how students learn to design in recent engineering education research initiatives. Yet, designing solutions to engineering problems requires a sound background in domain-specific conceptual knowledge.

The development of disciplinary knowledge is one of the key dimensions of becoming an engineer (Stevens, et al., 2008). The first outcome stated by ABET (the accreditation organization for undergraduate engineering programs) for an engineering program states students must have "an ability to apply knowledge of mathematics, science, and engineering" (ABET, 2017). While each discipline does not have a list of required courses, ABET suggests topics that should be included in each discipline. For example, ASME through ABET requires mechanical engineering programs to provide opportunities for their students "to apply principles of engineering, basic science, and mathematics; to model, analyze, design, and realize physical systems, components or processes; and prepare students to work professionally in either thermal or mechanical systems while requiring topics in each area." Each school has its own structure of teaching these topics through required and elective courses. Many follow the structure

beginning with a “cornerstone” design course in the first year along with basic math and science courses and end with a capstone design project linking engineering courses to real world practice (Lord & Chen, 2014). The “middle years,” as labeled by Lord and Chen, are full of courses that “impart discipline specific content – content needed to become an engineer” (p. 182). These engineering science courses can be construed as building students’ toolbox for their future engineering career; yet, they are often disconnected from each other and involve little design. While some work has been done to improve these courses (Kober, 2015; Koretsky, 2015), at many institutions, most courses still follow lecture-based pedagogies and assign problem sets with well-structured problems (Freeman, et al., 2014).

Educating an engineer is a complex system. Students follow a semi-prescribed path through their courses at their chosen institution. These courses are taught by faculty that have many different ideas about how students obtain knowledge and how to structure their course, activities, and assignments. Students also enter engineering school with preconceived attitudes about school and learning as well as different identities, epistemologies, and framings that influence how they learn in a classroom (Danielak, Elby, & Gupta, 2014; Hammer, Elby, Scherr, & Redish, 2005). It would be beyond the scope of a single research program to analyze every aspect of this system. In this dissertation I focus on homework assignments in engineering science courses and student epistemologies related to those courses.

1.2.1 Conceptual Knowledge

Numerous studies have shown gap in students’ conceptual knowledge in engineering (Streveler, Litzinger, Miller, & Steif, 2008; Montfort, Brown, & Pollock,

2009; Reed-Rhoads & Imbrie, 2008) and in physical sciences important for engineering domains (McDermott, 1984). Streveler and colleagues (2008) reviewed studies of engineering graduates' conceptual knowledge of mechanics, circuits, and thermodynamics and found gaps in all three, especially the thermal sciences. Montfort, Brown, and Pollock (2009) found through multiple choice conceptual questions in interviews that students ranging in level from sophomore undergraduates to graduate school had similar levels of conceptual knowledge; the graduate students were just able to solve problems faster.

One way engineering educators have proposed to work on the conceptual gaps in students' knowledge is through the creation and use of "conceptests" and concept inventories (Koretsky et al., 2014; Reed-Rhoads & Imbrie, 2008; Lord & Chen, 2014). These collections of questions are used to help students develop or assess a particular set of conceptual knowledge. "Conceptest" concept questions are formative: they are used for instructional purposes. Koretsky and colleagues (2014) suggest using their large online warehouse of chemical engineering conceptual questions during class time and for homework assignments. Vigeant and colleagues (2016) have created inquiry-based activities to teach difficult concepts in heat transfer to improve performance on the corresponding inventory. Concept inventories are summative: they are used for evaluative purposes. Instructors administer concept inventories as pre-post evaluations to understand the learning gains of students during particular courses (Steif & Hansen, 2006; Steif, Dollár, & Dantzler, 2005; Bristow et. al., 2012).

Despite these initiatives, there is not substantial evidence that these instructional tools and assessments are in widespread use outside of innovative, reform-minded

programs. Research teams using concept inventories as a diagnostic tool report common gaps in student knowledge in evaluated domains but few report pedagogical reforms initiated by the research team or faculty to increase student conceptual knowledge.

Another attempt to improve learning of conceptual knowledge is through Model Eliciting Activities (MEAs). Originally created for math concepts (Hamilton, Lesh, Lester, & Brilleslyper, 2008), MEAs are real-world client-driven problems that ask students to use engineering concepts to create one or more solution in the form of a mathematical model (Diefes-Dux et. al., 2004). Each MEA focuses on a specific concept that is part of a domain of knowledge. For example, van Bloemen Waanders, Kean, and Self (2011) created an MEA for teaching thermal efficiency in an introductory thermodynamics course by asking students to create a model of and evaluate an engine cycle.

Concept questions and model-eliciting activities can be seen as complementary approaches for engineering learners. By working with concept questions, students and faculty can identify key sub-domains of conceptual knowledge and pinpoint their strengths and weaknesses in reasoning with that knowledge. Model-eliciting activities can then provide rich contextualized opportunities to leverage strengths and address weaknesses in conceptual knowledge.

While model-eliciting activities represent one possible solution to the problems that concept inventories reveal, I aim in this dissertation to explore the root causes of those problems. By searching for the sources of engineering students' struggles with conceptual knowledge, I hope to contribute insight on how to overcome those struggles.

In the next chapter, I describe the theoretical perspectives on learning that ground my work, and I explain how the dissertation is organized.

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2.1 Theoretical Framework

This chapter outlines my theoretical and methodological frameworks for this dissertation. My work is grounded in a social constructivist perspective: individuals construct their knowledge through interactions with others individuals and objects in the world (Piaget & Inhelder, 1969; Vygotsky,1962). Learning requires making sense of new ideas based on prior knowledge and experiences. The contexts in which people learn concepts influence how they are activated or recalled later.

Consistent with constructivist theory, I also view learning as a process that depends on the activation of learners' *resources* as well as learners' *framing*. Resources are little pieces of knowledge which students call upon to form a new idea or understanding(Hammer, Elby, Scherr, & Redish, 2005; Smith, diSessa, & Roschelle, 1994). If a student is thinking about how gravity influences the motion of a particular object, they might have resources such as a physics teacher dropping a ball, the value of 9.81 meters per second squared, or an arrow pointing downward. Different resources may be cued by different contexts or framings. A *framing* (Tannen, 1993) is a set of expectations one has about a situation. Epistemological framing is how one expects to use knowledge in a certain situation (Scherr & Hammer, 2009). For example, one would have different framings about how to use the resources they have about gravity when walking into a physics classroom versus watching a small child play on a tall platform on the playground. In one case you might need to recall the value of gravity, while in the other you only need to know to watch to make sure the child doesn't jump. Research has shown the framing of an interaction is influenced by moment-to-moment cues in the environment (Scherr & Hammer, 2009).

Thinking about resources and framing can help us understand apparent cases of student confusion in engineering courses. For example, consider a case in a fluid mechanics course where a student becomes confused about the impact of gravity on a system. Three students are learning about Bernoulli's equation and are asked to solve a problem with a series of pipes in a U shape exiting a tank. The students are creating a mathematical representation of the spout of the water shooting out of the end of the pipe. Most likely these students have resources for thinking about water shooting out of a pipe, including everyday experiences with sinks and showers, seeing a fountain in a city park, or taking a sip out of a drinking fountain. They also have resources for thinking about gravity such as dropping a ball or using the value of 9.81 m/s^2. A single student even displays these resources in discussion by talking about kicking a ball and gravity's effect on it. Activation of particular resources might come from the students' framing of the situation. The students are in a university computer lab with their textbooks open, graphing calculator on, and homework problem in front of them. Students may frame this situation as the task of completing their homework. They may also frame this situation as figuring out fluid mechanics. Analyzing student discourse to understand their framing of the situation may help us understand what resources are or are not activated, and how that activation or lack thereof influences how students analyze and solve the homework problem.

This dissertation looks at how students learn domain-specific knowledge in the engineering sciences, which is knowledge strongly based in the application of science and mathematics principles to physical systems. Examples of engineering science domains of knowledge are fluid mechanics, control systems, thermodynamics, and solid

mechanics. This dissertation will use the phrase *conceptual knowledge*, as used by Streveler and colleagues (2008), to encompass both key concepts and approaches to applying those concepts used in the domain. Other authors may refer to this as conceptual understanding (Yadav, Vinh, Shaver, Meckl, & Firebaugh, 2014), or engineering as knowledge (Sheppard, Colby, Macatangay, & Sullivan, 2006).

2.2 Methodological Approach

The methodology for the studies in this dissertation is a qualitative descriptive approach, which allows for detailed exploratory investigation of rich, real life phenomena. In qualitative studies that include both observation and interviews with participants, researches can identify and tease apart the multiple ways people make meaning of the world around them (Merriam, 1998). In this dissertation, my key data sources are video recording of academic interactions (homework sessions) and retrospective interviews with the participants in those interactions. Through fine-grained examination and qualitative description of these data sources, I can uncover mechanisms that would remain hidden if the academic interactions were only measured by numbers and averages. While detailed qualitative research requires smaller sample sizes that appear to limit the generalizability of potential findings, researchers can triangulate their analyses with more than one data source to ensure their findings are trustworthy. Qualitative research with participant interviews also allows for consideration of context – a participant's background and the way they look at the world.

2.3 Analytical Framework

In this dissertation I draw heavily on discourse analysis to take a microethnographic approach to examining episodes of students working on homework

and subsequent interviews (Goodwin, 1990; O'Connor & Michaels, 1996). I examine episode transcripts line by line, using the above and below lines of the conversational triplet to understand context (Pearce, 2007). When a student's or group's sequence of ideas cannot be deciphered from a transcript alone, I return to the video to review short excerpts.

The following sections will present a brief overview of the three primary analytical lenses used in my dissertation. Then, I will outline the three chapters of the dissertation and more specifically how each of these lenses is used to analyze the data.

2.3.1 Task Production and Knowledge Construction

Inspired by Koretsky and Nolen's analysis of chemical engineering senior design teams, I used the constructs of *task production* and *knowledge construction* as analytical tools for understanding what students are doing during a homework session (Koretsky, Nolen, Gilbuena, Tierney, & Volet, 2014; Volet & Vauras, 2013). Task production is talk focused on accomplishing a procedural task such as manipulating variables, computing mathematical operations, or comparing answers. Knowledge construction is talk focused on making meaning such as relating physical quantities to variables and equations. Analyzing the data, it emerged there were also utterances that were *bids* for knowledge construction, when a student made a statement indicating to his or her peers they wanted to make sense of something. In some most cases, students in the group took up the bid to have a conversation, but in others, the bid was rejected or ignored.

Kittleson and Southerland (2004) similarly examined student discourse in a capstone design course for *concept negotiation*, or group conversations about

understanding the science concepts, and *procedural project talk*, or group conversation about the logistics of completing the project.

2.3.2 Epistemological Framing

I paired the analytical tools of task production and knowledge construction with an examination of *epistemological framing* (Bing & Redish, 2009; Hammer, Elby, Scherr, & Redish, 2005), which describes how a student is expecting to use knowledge in a certain situation. Bing and Redish (2009) analyzed video of physics students doing homework and showed how students' different epistemological frames caused misunderstandings in group work sessions. Attending to students' framing can help instructors understand difficulties in student problem solving. When researchers analyze student interactions for epistemological framing, they use discourse cues to determine the student's sense of "What is going on here?": the answer to that question indicates what kind of frame a student may be in at a given moment (Hammer, Elby, Scherr, & Reddish, 2005). A student uttering "wait, that doesn't make sense" indicates a different framing of the activity than a student saying "Great, that matches the answer in the back of the book!" However, cues of a students' framing are not usually that direct. In my analysis, I looked at a student's sequence of utterances across the homework session to determine their sense of the purpose and aims of working on the homework tasks.

2.3.3 Productive Disciplinary Engagement

Productive disciplinary engagement (PDE) was the third key analytical tool that I employed to study homework episodes (Engle & Conant, 2002; Engle, 2011). This construct aids in identifying "moment-by-moment development of new ideas and disciplinary understandings as they unfold in real-life settings (p. 403; Engle & Conant,

2002).” PDE moments can be identified by examining signs of engagement and use of disciplinary language, and by following student thinking and identifying intellectual progress – that is, advances in conceptual understanding. As outlined by Engle (2011), signs of engagement include students attending to and building off each other’s ideas, gesturing, or making emotional displays. Moments of PDE are set apart from other task-related talk in engineering science homework sessions by the integration of talk, physical behavior, and mathematical representations to make sense of or model a physical situation. Markers of intellectual progress are identified by pairing the worked answer to a problem with students sense-making talk and tracking their ideas from beginning to end of the time they spend on the problem.

Research on productive disciplinary engagement is related to research on disciplinary practices, such as constructing explanations and participating in argumentation. Other studies in science education have highlighted the importance of students forming explanations and arguments with evidence in order to articulate and make-sense of their understandings of phenomena (Berland & Riser, 2009). Research in middle and elementary school classrooms highlights the importance of having students talk to each other in order to form their arguments instead of expecting all discussion to occur through exchanges with a teacher (Duschl et al., 2007). When educators support student participation in explanation construction and argumentation with evidence, they are setting the stage for productive disciplinary engagement.

The construct of productive disciplinary engagement is key to this thesis research because my goal is to come to a better understanding of whether, when, and how students are engaging with conceptual knowledge during homework sessions. Markers of

productive disciplinary engagement to help identify instances of *sense-making*, which can lead to deep learning of engineering conceptual knowledge within these homework sessions. In the section below I define sense-making in the context of this thesis.

2.3.4 Sense-making

As mentioned above, science education researchers such as Michaels, O'Connor, and Resnick (2008) and Berland and Riser (2008) call for students to participate in the discourse of science to build knowledge by constructing explanations and arguments. When forming explanations and arguments, students have to activate their everyday and scientific resources and articulate how they make sense of phenomena and disciplinary ideas. In this study, I looked for conversations between students attempting to *make sense of* phenomena related to the homework problems they were solving. Sense-making conversations are "seen as the primary mechanism for promoting deep understanding of complex concepts and robust reasoning" (Michaels, O'Connor, & Resnick, 2008). Identifying these conversations is key to understanding how students may form ideas about conceptual knowledge during homework sessions.

2.3.5 Connected the Analytical Lenses into a Framework

The goal of the three related studies in this thesis is to identify instances when engineering students are highly engaged in disciplinary talk during homework sessions. In Engle and Conant's paper on productive disciplinary engagement (2002), they outline four elements of an activity that would create the best conditions for PDE to occur: authority, agency, accountability, and resources. None of these elements is typically built into assigned engineering homework problems, so I had little expectation of seeing many instances of PDE. Since the research literature tells us little known about how students

talk, and what they talk about, while working on homework, the goal was to characterize all parts of what students were doing. To do this, I began analysis with the task production and knowledge construction coding scheme. Segments coded as knowledge construction were examined further to determine if the students were sense-making or making a *bid* for sense-making. A bid is a question or a statement indicating a student wants to make sense of a concept, variable, or situation in the homework. Students talking to making sense of a concept supports their constructing knowledge about that topic.

I used epistemological framing in conjunction with coding for task production and knowledge construction to examine utterances for evidence of how students were using knowledge during the homework session. While the constructs of task production and knowledge construction helped me to identify the goal of a particular student (in the form of a bid) or group of students (an episode) in the moment, examining students' framing helped me to identify what they thought they should be doing during the task. In many instances, we see these two dimensions aligned: students are framing a homework session as an opportunity to understand concepts, and they are engaged in knowledge construction. Other times, we see these dimensions in conflict: a student is framing the assigned homework as a task to complete, but a different group member is making a bid to sense-make and for a moment they both engage in knowledge construction. Identifying these tensions is important to understanding the work that gets done in the conversations students have, and if those conversations lead towards building conceptual knowledge.

2.4 Research Context

This research was conducted at a small, private, R1 university located in the Northeastern United States. It is a highly selective institution with 5500 undergraduate students. The engineering school is one of two undergraduate schools and has approximately 850 undergraduate students. Participants for this research were recruited from two engineering science courses that are required for a bachelor of science degree in mechanical engineering and taught by full-time professors in the mechanical engineering department.

Recruitment announcements were made during class sessions. Once consent forms were collected, I determined via notes on the consent form or e-mails which students worked together on their homework. I asked the student group via e-mail if I could video record them while they did their homework, starting with students who I knew from my lab or classes where I was the teaching assistant. If the students agreed, a time was arranged. I did not give students any specific instructions about how to go about doing their homework.

In total, seventeen students were video recorded during their homework sessions, and eleven students are featured subjects of the research reported in this dissertation. The six eliminated participants were in two homework sessions that were eliminated from the data set because of poor quality of the video data and little discourse between participants. Of the remaining eleven participants, eight students were working toward a bachelor of science in mechanical engineering and three students were working toward a bachelor of science in biomedical engineering. Eight participants were female and three were male.

This gender ratio is atypical for a study of engineering students. Despite females only making up one-third of the Tufts engineering school population and one-fifth of engineering schools nationally (Qu, 2017), almost three quarters of my participants were female. There may be a few reasons behind this. I personally solicited for participation in front of these courses. Women may have seen a fellow female engineer and been more inclined to help. Second, when reaching out to groups in the fluid mechanics course, I began with women I knew from work at my lab or whom I had previously mentored.

2.5 Overview of this dissertation

This dissertation is comprised of three related but distinct research studies. The goal is to understand whether and how students develop conceptual knowledge through discourse during homework sessions for engineering science courses.

The first study examines one homework session from a controls systems class. I present and develop a novel methodological approach to analyze the dynamics of homework sessions through using a established coding system and confirm those findings with retrospective interviews. This chapter presents initial results of the substance of student discourse during homework sessions and the development of the novel methodological approach. The two questions I aim to answer are:

1) How can we identify examples of mechanical engineering undergraduates using and developing their conceptual knowledge during homework sessions?
2) What does fine-grained video analysis show us about how students engage in sense-making during homework sessions?

The second study uses the novel methodological approach developed in the first chapter to analyze five fluid mechanics homework sessions and then examines small

excerpts to understand the triggers of student sense-making. This chapter also explores how students construct knowledge through explanations and arguments. The questions I aim to answer in this study are:

1) What does it look like when students engage in sense-making discourse during mechanical engineering homework sessions?
2) What are the triggers of sense-making during homework sessions?
3) How often do students shift to sense-making during problem set sessions?

The third study examines the retrospective interviews to understand what students think counts as knowledge in engineering, how they think they best develop knowledge, and which pedagogical choices they think help them develop knowledge. In essence, I am trying to understand student epistemological stances toward engineering tasks. The questions I aim to answer are:

1) What do upper-level undergraduate mechanical engineering students think counts as engineering knowledge?
2) How do upper-level mechanical engineering students think they develop that engineering knowledge?
3) What pedagogies choices by the instructor – both during class time and for out-of-class assignments – do students notice and regard as productive for their development of engineering knowledge?

I conclude the dissertation by discussing its major contributions, further directions for research, and suggestions for instructors in engineering classrooms.

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Chapter 3: Student Emphasis of Task Production in a Control Systems Homework Session

3.1 Introduction

Constructing and applying conceptual knowledge about physical systems is a core activity of practicing mechanical engineers. Accordingly, most undergraduate education programs in mechanical engineering are organized by domains of conceptual knowledge, such as fluid and thermal systems, statics and dynamics, and the mechanics of materials. However, despite coursework being organized by conceptual knowledge domains, a surprising proportion of graduating engineering students respond to conceptual questions by recalling fragmented facts and equations; they struggle to reason systematically about the causal mechanisms that drive a phenomenon (Streveler, Litzinger, Miller & Steif, 2008). Prior work has documented these problematic learning outcomes (Baillie, Goodhew, & Skryabina, 2006), but more research is needed to shed light on the sources of these fragmented conceptual understandings, especially in engineering science courses.

Courses in the engineering sciences (e.g. thermodynamics, fluid mechanics, control systems) typically have a lecture-based pedagogy (Kober, 2015). Lectures are usually followed by regularly assigned problem sets that ask students to apply the content of the last few lectures and are completed outside of class time. Problem sets are usually comprised of problems from the course textbook or written by the professor. Typically, the problems require mathematical modeling but may also include using software to produce graphs or simulations. Although length varies by instructor, a problem set typically takes several hours of work (and in the U.S., a 3-credit hour college course assumes 6 hours per week of out-of-class effort). Despite the frequency of this type of

assignment and the substantial number of hours undergraduate engineering students spend engaging with these assignments, there has been little research into how students approach and learn from these problem sets. This study aims to begin to understand how students work through problem sets and when and how students use and develop conceptual knowledge and reasoning skills during their work on problem sets. This initial study examines one homework session from a control systems course to address two methodology-oriented research questions:

1) How can we identify examples of mechanical engineering undergraduates using and developing their conceptual knowledge during homework sessions?

2) What does fine-grained video analysis show us about how students engage in sense-making during homework sessions?

To answer these questions, we need a systematic way of analyzing homework sessions for engineering science courses. In this chapter, I first look to methods used previously to examine student discourse during engineering design problems and engineering mathematical problem solving. I then propose combining (a) a method used in prior work to analyze students' sense-making during an engineering design task with (b) a novel approach to retrospective interviews. This combination enables me to triangulate discourse analysis results with students' self-reported perceptions. The purpose of this paper is to present a methodological approach and illustrate its application in a small case study. In the subsequent study, reported in Chapter 4, I apply the approach developed below to a larger data set.

I begin by reviewing methods which have been used in previous literature to analyze students' engineering problem solving. Next, I describe my methodological

approach to analyzing engineering students' sense-making during homework sessions. I apply the approach to a single homework session and describe the learning dynamics that it reveals. Finally, I discuss our findings, next steps, and implications.

3.2 Literature Review

Undergraduate students are asked to solve a variety of different types of problems during their undergraduate career, from well-defined textbook problems assigned as homework to ill-defined problems such as capstone design projects (Jonassen, Stobel & Lee, 2006; Jonassen, 2014). There is extensive work on how students solve problems through the steps of the engineering design process using think-aloud protocols (Atman, Cardella, Turns & Adams, 2005; Atman, Chimka, Bursic, and Nachtmann, 1999), classroom observations (Swenson, Portsmore, & Danahy, 2014; Welch, 1999), and identification of novice and expert behaviors (Crismond & Adams, 2012). These analyses and results are important for understanding how students are prepared to solve workplace problems, which are more like ill-structured design problems (Jonassen, 2014). However, they do not explain how students develop conceptual knowledge through problem solving.

Koretsky and Nolen's (2014) work provides a useful framework for analyzing engineering student discourse for conceptual knowledge construction. They analyze the student-to-student discourse of senior design teams working on a chemical engineering capstone project. They characterize this discourse as either *task production*, student talk directed at making progress on an assigned task, or *knowledge construction*, student talk centered around making sense of concepts (a distinction originally presented by Volet, Vauras, Khosa, & Tuike, 2013). Koretsky and Nolen's analysis found instances of sense

making triggered by "productive friction" that happened when constraints and components of the students' design conflicted.

In a similar study, Kittleson and Southerland (2004) investigated how a single team of engineering students constructed engineering science knowledge when working on a semester-long engineering project. The team they observed was working on analyzing and improving an automotive defroster for the Ford Motor Company in a class titled Design of Complex Continuum Systems. The authors were looking for "collaborative interaction in which more than one participant actively contributes to the evolving conceptual content of the conversation (p. 271)," an activity they called *concept negotiation*. The following excerpt, in which students are taking data on the automotive defroster, is one instance characterized by Kittleson and Southerland as concept negotiation. It can also be characterized according to the constructs of task production and knowledge construction. To explicate Koretsky and Nolen's coding scheme, I present the Kittleson and Southerland transcript and then explain whether and why it constitutes knowledge construction and task production as defined by Koretsky and Nolen.

1 Lance: (speaking to Kyle) It's really weird. What do you think? This, uh, for the stagnation point agrees with the temperature profile, but they both disagree with the tufts.

2 Kyle: That's weird.

3 Lance: Isn't that weird?

4 Kyle: So that agrees with the temperature from the infrared camera?

5 David: Yeah.

6 Kyle: Maybe the tufts introduce something that (David: Yeah, that could be it.) isn't actually there.

7 David: I don't know, it's kinda weird.

8 Lance: I don't know, the tufts though, they were pretty distinct. I mean there was, it doesn't look like they could go either way.

9 Kyle: I mean maybe they changed the flow somehow.

10 Lance: And this funny, this center point, I bet those tufts detect the first part of the jet, right where it hits.

11 David: That could be it, too.

12 Kyle: That's, uh, interesting.

13 Lance: So the tufts, you know, they split right when the jet, the first part of the jet, the

14 David: I bet you if you measure that, seems about right too. Let's do that real quick.

(Kittleson & Southerland, 2004, p. 277)

Consistent with Kittleson and Southerland's classification of this discussion as *concept negotiation*, I would code these lines as utterances of *knowledge construction* under Koretsky and Nolen's coding scheme. The first and second lines by Lance ("What do you think?") and Kyle ("Isn't that weird?") respectively I would identify as *bids* to the group to make sense of the data they just collected. The students are trying to determine if introducing the tufts measurement device affected the jet flow in unforeseen ways. To make sense of these results, they are comparing the tufts data to the infrared camera data,

and decide to employ another data collection technique to confirm their intuitions. To analyze these results, students are accessing fluid mechanics conceptual knowledge.

While Koretsky and Nolen's and Kittleson and Southerland's frameworks are helpful, they were developed when analyzing student work on ill-defined engineering design problems. My study's context involves more highly-structured engineering science problems. To illustrate the applicability of knowledge construction and task production framework for my context, I turn to other problem-solving literature that focuses on students work on textbook problems. One group of researchers (Lee, McNeill, Douglas, Koro-Ljngberg, & Therriault, 2013) used think-aloud protocols to examine senior materials engineering students' use of textbooks during problem solving. They found students "view problem solving as looking up a series of equations in the textbook" (p.285). They identified students using their textbooks during problem solving to search for formulas and material properties as well as to work backward through example problems to determine the next step they should take. Unlike the transcript above where engineering students attempt to make sense of a physical system, the materials engineering students' use of equations is more aligned with task production. This interpretation is supported by the researchers conclusion that the students lacked the conceptual understanding needed to solve the problems and instead depended on the textbook to provide them with equations and examples to help them solve the problem (Lee et al., 2013).

In a study by Litzinger et.al. (2010), students taking a statics course were asked to solve three statics problems using a think-aloud protocol. Researchers scored students' solutions and examined their metacognitive processes and self-explanations. Self-

explanations include when a student applies a domain-specific concept to the problem or an explanation directed at understanding the structure of the problem. They found students with higher scores used many more self-explanations than the students with lower scores. This application of concepts or developing explanations to understand the problem is more aligned with knowledge construction. To confirm this interpretation, I look at the evidence the researchers present. They describe how students attempt to solve a problem that asks them to draw the free-body diagram of an inclined ladder with a man standing on it. Litzinger et.al. (2010) discussed how Student 58 attempted to reason physically:

> "[The ladder]'s in a corner. That's a bit tricky because my first thought was that usually you don't see, like I haven't seen too many things in a corner. So it kind makes me think there might be one pointing over and also up. But another part of me says that (unintelligible). If it's on the ground there is just a normal force at like whatever direction it is touching the ground at."
>
> (Litzinger et.al., 2010, p. 344)

Above, we see that the student is not rushing to make progress on the task by immediately turning to his notes or looking up sample problems, but is instead pausing to make sense of the provided diagram and to identify relevant concepts like normal force. The student is analyzing a scenario he recognizes he has not seen before – a ladder jammed into a corner. He does not have a strong intuitive sense for the reaction forces on the edges of the ladder, and therefore he proposes two different free body diagrams to consider: one with just a single normal force and one with two in different directions. By proposing and comparing these alternatives, he is trying to make sense of the problem

scenario. This sense-making and many of the self-explanations that Litzinger et al. found in the think-alouds of stronger problem solvers could be characterized as knowledge construction talk.

These previous studies and my brief re-interpretations of episodes of their data suggest the task production and knowledge construction framework can be applied to engineering homework sessions to identify students making sense of concepts. This literature lays the foundation for addressing my first research question (RQ1): *How can we identify examples of mechanical engineering undergraduates using and developing their conceptual knowledge during homework sessions?*

My second research question is motivated by an alternative approach to investigating students' conceptual work as they tackle science or math problems. Lee et.al. (2013) and Litzinger et.al. (2010) illustrate that much can be gained from think-aloud studies in which students are specifically asked to verbalize their thinking as they work. However, another approach that has been fruitful in physics education research is to conduct fine-grained video analysis of video collected as students work naturalistically on homework problems. Two studies of physics students working on homework gives us insights into how this method can help us understand learning dynamics in engineering science courses.

Tuminaro and Redish (2007) examined eleven hours of students solving algebra-based physics homework problems together. To interpret students' interactions, they used the construct of epistemic games, which they defined as "a coherent activity that uses particular kinds of knowledge and processes associated with that knowledge to create knowledge or solve a problem" (Tuminaro & Redish, 2007, p.4). The authors found and

characterized five unique epistemic games within their data: mapping meaning to mathematics, mapping mathematics to meaning, physical mechanism game, pictorial analysis game, and recursive plug-and-chug. Of the five epistemic games, four involve the use of conceptual knowledge such as the "development of the conceptual story" about the physical situation (p. 6-7). These four epistemic games all include knowledge construction activities. Because they emerged from hours of transcript from student groups solving homework problems, they illustrate different ways students were using knowledge and reasoning to solve homework problems. On the other hand, the recursive plug-and-chug epistemic game – described as one where students "do not attempt to understand conceptually what the quantity physically" (p.8) – features task production activities. Overall, Tuminaro and Redish's study shows that the rich in-situ data of students solving actual homework problems "gave [the authors] an authentic look at how students actually behave in real-world problem-solving situations – as opposed to watching them solve problems artificially posed to them in an interview environment" (p.9).

A study by Bing and Redish (2009) examined similar video of students doing homework in a calculus-based physics course. In this study, the authors examined the students' epistemological framing, or "student's perception or judgment as to what class of tools and skills is appropriate to bring to bear in a particular context or situation" (p.1). They found students engaged in a disagreement about how to solve a problem because the students each framed their activity differently and were not recognizing each other's claims. "When there is a disagreement, the discourse tends to include warrants – reasons for drawing conclusion" (p.1). These warrants illuminated which epistemological

framings the students were in. By looking across data where groups disagreed, the authors were able to distill four common framings: calculation, physical mapping, invoking authority, and math consistency. While these framings are a little harder to map to task production and knowledge construction than the epistemic games, there are hints to which types of activities that they might include. For example, a calculation framing which is defined as "algorithmically following a set of established computational steps" (p.7) would probably lend itself to more task production activities while a physical mapping framing, defined as "a math…representation…characterizes some feature of the physical…system it is intended to represent" (p.7) probably includes knowledge construction activities.

Using discourse analysis of in situ group homework sessions, these two studies (Tuminaro & Redish, 2007; Bing & Redish, 2009) reveal the dynamics of different types of task production and knowledge construction activities by students. Additionally, these studies demonstrate that the activities in which students see themselves participating are negotiated among peers. I argue that such fine-grained analyses can reveal not only the types of knowledge-related activity in which students themselves engage, but also the ways in which students influence their peers' knowledge-related activity. For example, if a student is in a group with another student who believes making sense of the material is part of the process of doing homework, the first student may participate in more sense-making conversations than if they were working alone. I develop this argument by answering my second research question (Q2): *What does fine-grained video analysis show us about how students engage in sense-making during homework sessions?*

This study combines the findings reviewed above with Koretsky and Nolen's (2014) definitions of task production and knowledge construction to guide an analysis of whether and how undergraduate engineering students are developing knowledge during engineering science homework sessions. The purpose of this analysis is a "proof-of-concept" of an approach to analyzing homework session discourse.

3.3 Methods

3.3.1 Participants

The participants in this study, Chloe, Sophia, and Aurora, were mechanical engineering students in their third year of college at the start of data collection. They were recruited for this study during a session of their control systems class. On their research participation consent forms, they listed each other as peers with whom they commonly worked on homework. I sent an e-mail to ask if I could observe and video record their homework sessions. All three students were high performing students both in the controls class and their college courses overall (Table 3.1).

Table 3.1: Subject academic performance in controls class and overall coursework

Name	**Grade Range in Course**	**Overall GPA Range**
Chloe	A/A-	3.7-4.0
Sophia	A/A-	3.7-4.0
Aurora	A/A-	3.3-3.7

3.3.2 Course Context

Control systems is a required course for the undergraduate degree in mechanical engineering and is typically taken in the spring semester of the third year. The course has two 75-minute lectures per week and the students are assigned a weekly problem set. Five class periods during the semester are designated for in-class laboratory exercises. The lectures are designed around students filling in "skeleton notes" provided by the

professor; these notes are intended to serve in place of a textbook for the course. Students can also download completed notes from the course website after the lecture. A textbook was listed as a reference on the course's syllabus but none of the participants I video recorded ever mentioned using this book as a potential reference. Coursework emphasized procedural problem solving and developing mathematical tools. The professor held office hours once a week for two hours the night before the homework was due. Students were highly encouraged to attend. The teaching assistant also had office hour for one and a half hours two days a week.

3.3.3 Task

The task the students worked on during the recorded video session was the fourth problem on the eighth assigned problem set of the semester. The problem statement is as follows.

4. (25 points) The input signal and output signal at steady state for a first order linear time invariant system for several different input frequencies are shown below.
   a. For each plot, determine the input frequency ω, the input amplitude A_i , the input phase ϕ_i, the output amplitude A_o, the output phase ϕ_o, the magnitude $M(\omega)$, and $\phi(\omega)$.
   b. Assuming the transfer function of the system is $G(s) = \frac{K_{DC}}{\tau s+1}$, which plot corresponds to an input frequency of $\omega = 1/\tau$?
   c. From which plot can you estimate K_{DC}?
   d. Plot the entire Bode plot using MATLAB.

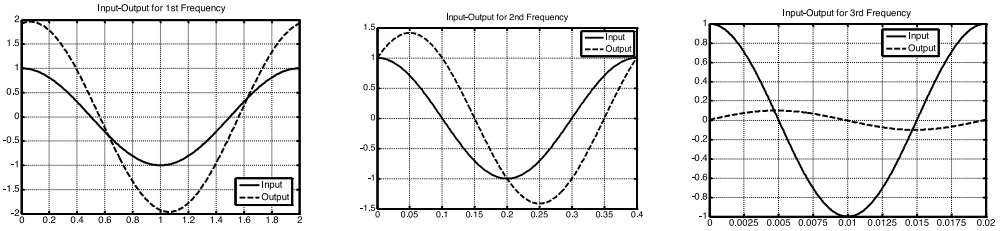

Figure 3.1: Controls Homework Problem

The first part of the task asks the students to analyze three input/output signal plots and determine a number of different values related to the signal. Parts B and C ask the students which of the plots best corresponds to the scenario presented. Lastly,

students are asked to create the Bode plot, or the frequency response plot for magnitude and phase shift, for this signal. Chloe, Sophia, and Aurora spent 51 minutes on the task (parts A through D). An outline summarizing how the students spent their time on each of the different aspects of the problem during their homework session is shown in Table 3.2.

Table 3.2: Summary of Control Systems Homework Session

Time (minutes)	Student Work
0 to 14	The students work on part a for the first plot
14 to 19	The students work on part a for the second plot
19 to 20	The students go back and discuss one answer from the first plot
20 to 22.5	The students work on part a for the third plot
22.5 to 24.5	The students have an off topic conversation but still seem to be doing minor calculations on their homework
24.5 to 26.5	The students shift the conversation back to part a for the third plot
26.5 to 30	Off-topic conversation
30 to 31	The students begin to work on part b
31 to 32	Off-topic conversation
32 to 32.5	The students decide they can't finish part b
32.5 to 46.5	Off-topic conversation
46.5 to 49	Silent work
49 to 51	Working on problem 3 of the problem set

3.3.4 Data Collection

This study was conducted at a small private university in the northeastern United States. I attended one class session of the control systems course each week and video recorded all the in-class laboratory sessions of groups of students consenting to participate in the study. I also recorded three homework sessions of three different groups of students. Chloe, Sophia, and Aurora's work on the input/output signal task was chosen as the focus of analysis for this case study because all three students were participating for the entire length of the homework session, and because the video recording captured their spoken conversation as well as their inscriptions on paper.

During the homework session, video was taken of each individual's paper and multiple views of their faces. The session lasted approximately 50 minutes. The students

did not finish the problem during the session because they concluded they needed help from the professor during office hours in order to finish solving the problem. I transcribed the homework session using one of the video recordings.

After an initial analysis of the homework session, I conducted retrospective interviews with each student at the end of their fourth year, just before graduation. The interviews began with a review of the problem the students solved in the homework session and the group dynamics in the homework session. Then I asked the student to compare the task to the other homework problems she had in the course, to determine if it was representative of the type of problems that were typically assigned, and then to other problems she had in their undergraduate courses. I continued this line of questioning by asking the student to describe the best task she had been given thus far in her engineering courses. I then switched back to asking about the homework problem the student solved on video, the dynamics of the homework group, and the student's perception of the goals and strategies she and her peers had for the homework session. I ended the interview by having the student read over the transcript of the homework session and reflect on the homework problem, the group dynamics, and the goals of the homework sessions again. By asking the questions in this order, I could prompt students both to recall their impressions from memory and to reinterpret their impressions after looking at the transcript.

3.3.5 Data Analysis

The transcript of the homework session was coded line by line using the coding scheme of task production and knowledge construction, originally proposed by Volet, Vauras, Khosa, and Tuike (2013) and used by Koretsky and Nolen (2014). I determined

which code to apply by examining discursive triplets (Pearce, 2007), looking at the line both above and below for context. The lines were coded as Task Production, Knowledge Construction, or Off-Topic (Table 3.3).

Table 3.3: Definitions and Examples of Codes

Code	**Definition from Koretsky & Nolen (2014)**	**Example from Transcript**
Task Production	Cognitive talk oriented at the completion of the set work that was prescribed by the instructor	Sophia: And what did you get for M omega?
Knowledge Construction (or a bid for Knowledge Construction)	Cognitive talk directed at making meaning, trying to build connections between ideas and understanding, and answering how and why questions	Chloe: Like what's the difference between phi omega and the other two?
Off-topic	Talk unrelated to the engineering task	Sophia: Just throwing my calculator around!

I worked with an engineering education faculty member to establish inter-rater reliability of the coding scheme. The faculty member was familiar with the coding scheme and was given one-fifth of the controls homework session transcript to code as second rater. The double-coded excerpt was selected because it appeared likely to require application of all three different codes and not just one or two of the codes. The results were compared and 85% of the codes were matching.

The retrospective interviews were analyzed using thematic analysis. First, I read through each of the interviews underlying portions of responses and writing notes in the margins about the themes in the utterance. Second, I read through the interviews with a focus on the students' use of the word "learning." For each student, I grouped similar utterances to develop my sense of that student's view on learning and assigned tasks in engineering. After reviewing the analysis of the homework session, I went back to the

interviews and examined responses to the specific questions about group dynamics, the student's goals, and their interpretation of the goals in the homework session. These responses were used to validate the results of the line-by-line coding and help further explain student behaviors during the homework sessions.

3.4 Findings

In the following sections, I present the findings in three parts. First, I summarize the coding results to illustrate the dynamics of student discourse during a homework session. Second, I show how the coding approach can help us better understand at a fine-grained level what is happening when students work on engineering homework together. In this section, I present a narrative analysis of one episode of the homework session where we see one student making a bid for a sense-making conversation. Third and finally, I show how the data from the retrospective interviews confirm the findings from the discourse analysis of the homework session.

3.4.1 Task Production and Knowledge Construction

The homework session was coded for turns of talk focused on making meaning (Knowledge Construction), completing the task (Task Production), or off topic comments (Off-Topic). I found that out of the 322 utterances during the homework session, 273 were aimed toward task production and 33 were aimed toward knowledge construction (Table 3.4). All knowledge construction utterances took place during the single segment presented in detail in section 3.4.2 below.

Table 3.4: Overall frequency of task production and knowledge construction turns of talk during a controls homework session

Orientation of student talk	**Task production**	**Knowledge construction**
Number of turns of talk	273	33

Table 3.5 provides the number of turns of talk related to task production and knowledge construction for different segments of the episode. The predominance of task-oriented utterances demonstrates that students were almost exclusively focused on trying to get the homework problem done.

Table 3.5: Chronological summary of control systems homework session with frequencies of task production and knowledge construction turns of talk

Time (minutes)	**Task Production**	**Knowledge Construction**	**Focus of Student Work**
0 to 4.75	62	0	The students work on part a for the first plot
4.75 to 7.75	4	33	Chloe makes a bid for knowledge construction, and the group attempts to answer her question but do not have the resources to answer it
7.75 to 9.25	9	0	The students continue working on part a for the first plot
9.25 to 14	43	0	The students come up with a way to solve for $\phi(\omega)$ but debate whether the answer should be in degrees or radians
14 to 19	59	0	The students work on part a for the second plot
19 to 20	22	0	The students go back and discuss one answer from the first plot
20 to 22.5	9	0	The students work on part a for the third plot
22.5 to 24.5	0	0	The students have an off topic conversation but still seem to be doing minor calculations on their homework
24.5 to 26.5	15	0	The students shift the conversation back to part a for the third plot
26.5 to 30	0	0	Off-topic conversation
30 to 31	21	0	The students begin to work on part b
31 to 32	0	0	Off-topic conversation
32 to 32.5	9	0	The students decide they can't finish part b
32.5 to 49	0	0	Off-topic conversation
49 to 51	18	0	Working on problem 3 of the problem set

To understand better why task production utterances dominated the conversation, I grouped them into three sub-categories of discourse moves that students used to move

forward procedurally in the homework session. The three main types of task production discourse were checking, calculation, and group direction. Checking moves were usually a pair of utterances where one student asked the other for their numerical answer followed by a response. Calculation moves involved utterances stating an equation or calculating a number out loud for their peers to follow their work. Group direction moves were statements focused on verbalizing what the group would do next. The following excerpt demonstrates both checking and calculation.

Checking	Sophia: So do you get 0.314?
Checking	Aurora: Yep.
Checking	Sophia: Otherwise known as *pi*?
Checking	Chloe: Divided by 10.
Calculation	Sophia: Is that what I need to do?
Calculation	Sophia: Oh divide by 10. Yeah, yeah, yeah. I'm like why do I have to divide by ten? Okay.

Group direction utterances included statements such as “Now we need phi in and phi out – so we still need phi in and phi out and M of omega, correct?” and “Alright there we go. Okay, shall we go to the second plot?”

3.4.2 A Bid for Knowledge Construction

Although the students’ interactions during the homework session mainly consisted of calculations, checking values, and logistical discussion of what to do next, the coding analysis did reveal one three-minute episode containing discourse oriented toward knowledge construction rather than task production. In this particular episode, Chloe makes a bid for knowledge construction. After a pattern of discussing equations

and answers, the purpose of the homework session discourse shifts based on Chloe's question: what's the difference between these three variables? This plea for help with sense-making starts with Chloe (Line 3) asking her peers to explain the difference between the three values they are solving for.

1 Aurora: Yeah, but M of omega is so simple.

2 Sophia: Peak to peak output amplitude.

3 Chloe: Wait, I don't see how this is different.

4 Aurora: What do you mean?

5 Chloe: Like what's the difference between phi omega and the other two?

6 Sophia: I'm not particularly sure.

7 Aurora: Oh wa-wa-wa-wait. I've written this down somewhere.

8 Sophia: What does peak to peak output amplitude mean?

9 Aurora: Yeah. No, no, look. Cause this is – so we have phi out equals phi in plus phi of omega. Okay, so I'm just getting this out of the way cause this is…

10 Aurora: But you can also do it this way but we don't have either phi out or phi omega.

11 Sophia: So that's a two.

In Line 3, Chloe interrupts the group's task production to ask her peers the difference between three quantities they are asked to find on the graphs: the input phase phi (ϕ_i), the output phase phi (ϕ_o), and phi of omega ($\phi(\omega)$). At this point she does not understand the difference between these variables and the importance they have to control systems. Before continuing the assignment, she wants to have a conversation

about each variable and how they are different, and makes a bid to do so (Lines 3 & 5). The assignment asks students to find values for these variables three times and Chloe believes she may be asked to use this information in the future for this class. Sophia echoes Chloe's bid by asking a question of her own (Line 8). Aurora tries to find an answer for Chloe's question by looking in her notes (Line 7, 9, & 10) but does not take up the bid to sense-make. Aurora's response is to find an answer, not to have a conversation to figure out an answer.

Chloe has reason to be confused. Phase indicates the lag between the beginning of the signal and the peak of the sine wave. Output phase is measured relative to input phase. Input phase is zero or measured off some other given benchmark. In this problem no benchmark is given, so asking students to "determine the input phase" is essentially a trick question; it's simply zero. Phase as a function of omega ($\phi(\omega)$) represents the difference between the input phase and the output phase at a particular frequency. Calculating it involves finding the time delay and reading the two values off the plots. (For the first plot, it's best to read the two values when they cross the zero line. Looking at the left most graph on Figure 4.1, we could approximate these values at .5 for the input signal and .55 for the output signal) Then, it needs to be converted into either radians or degrees. It's interesting Aurora's response to a question about the meaning of the variables is to read an equation from her notes (Line 9). The equation is not very helpful since input phase, phi in, is usually zero. They continue trying to understand whether there is a meaningful difference between the three variables.

12 Sophia: So can we like regroup for a second because I feel like everyone's on a different part.

13 Chloe: I don't get what you're talking about when you're saying that there's two different ones.

14 Sophia: So…

15 Chloe: Cause to me even looking at equations, to me it's like the same thing.

16 Sophia: What is the same thing?

17 Chloe: Like phis. Or like M(ω) is this....the same that?

Chloe attempts to clarify for the group what she wants to discuss. She expresses that equations found in her notes do not help her understand the differences between the variables. The attempt to understand the differences continues.

18 Sophia: Like why is there an input phase and an output phase and the phase omega?

19 Chloe: Yeah what's the difference between…?

20 Sophia: I - the only reason I think that the phase omega is this (points to equation on lecture notes) is because like on this part (points to a different page on the same lecture notes) that's what it was.

21 Aurora: Yeah, no, you're right about this being the…

22 Sophia: Do I know what the phase in and the phase out are? No.

23 Aurora: I think that input there's a zero phase input but the - you see how the output starts a little bit past the peak?

24 Sophia: Yeah.

25 Aurora: That would be the phase output, but I don't know.

26 Sophia: Like point one?

27 Aurora: Yeah.

At Line 18, Sophia takes up Chloe's bid for sense-making and restates her question: what is the difference between these three variables? Sophia attempts to find an answer, but explains the way she has determined this answer is based off what is in her lectures notes. In Line 22 her tone indicates her frustration of not being able to figure this out. Aurora jumps in with a possible answer and explains how she is determining the phase output. Her additional comment 'I don't know' (Line 25) shows even she doubts her answer. She's correct, but hasn't answered her peers' question with an explanation of the difference in the meaning of those three variables. Chloe and Sophia try and understand her proposed answer. In trying to determine if her answer is correct, they look back at the graphs and have a conversation about the units for the x-axis of the figures.

28 Chloe: But the bottom is in time.

29 Aurora: I know, so that's the only reason....that doesn't make sense.

30 Sophia: What is the bottom?

31 Chloe: It's got to be time...I don't know what else it would be.

32 Sophia: Yeah I think it is too.

The x-axis of each of the graphs is not labeled with units, and they come to a consensus about what the units are and the implications of those units to their answers.

33 Sophia: I agree with Aurora. I think one is the - the input is zero and the output phase might be point one. But I mean the....

34 Sophia: This was also the thing he was saying that we might want to like ...have that other lecture for. Like he sent in the e-mail saying like the first two

(out of four assigned homework problems) should be easy but the second two like you might want to wait 'til after the lecture tomorrow.

35 Aurora: Oh, he did say that.

36 Sophia: So like we can still - I think we should still do it and like if…

37 Aurora: I think we should leave phase output and phase input because we've calculated the M of omega, phi of omega, A i, and omega, so I think just wait to do phi input, phi output.

Sophia agrees with Aurora's responses, but the students still don't seem sure of their answers. They conclude that since their professor e-mailed and said they might want to have the information from the next day's lecture, they are going to wait until then to determine the phi input and phi output.

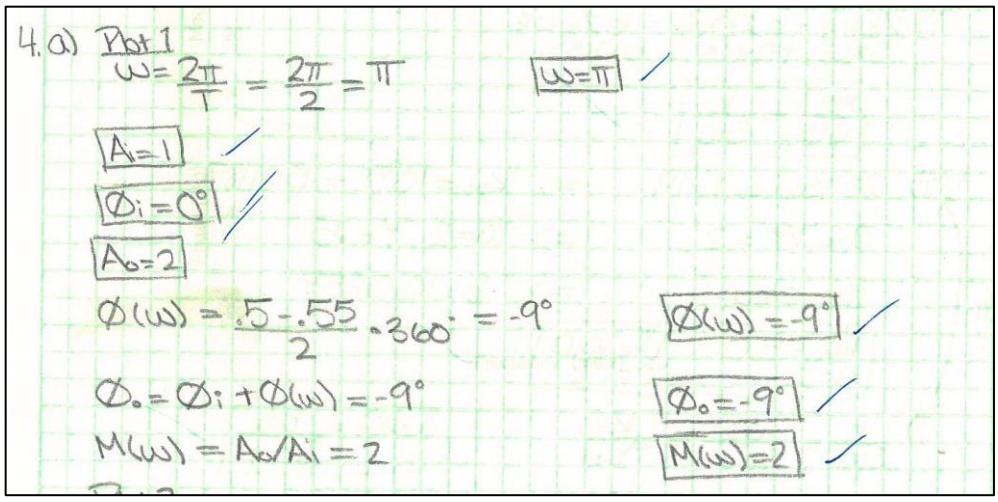

Figure 3.2: Copy of Aurora's homework for Problem 4, Plot 1

Examining the problem and their eventual answers on photocopies of their homework (Figure 3.2) it's confusing why this problem would take fifteen minutes and still not be completed by the group. Chloe, Sophia, and Aurora seem to be stuck in the strategy of searching for equations to complete the task (Lee, et.al., 2013) and do not take

a step back to understand what they are being asked to identify. This question is simply asking them to examine a signal and describe its behavior by identifying some of its properties – phase, amplitude, and frequency. When searching for an answer, they look to plug numbers into equations from their notes. Aurora tries to find the differences between the phase variables by locating an equation that shows a relationship between them instead of having a conversation to make sense of the differences. Sophia tries to copy the answer from a previous example in her notes. While interpreting the relationship modeled by an equation is a good sense-making practice in general, it would be more productive if they first asked themselves, "what do we know about *phase*?" Instead, they are stuck in framing the problem as a series of mathematical calculations. The structure of the course, with its skeleton notes released one lecture at a time in lieu of a textbook, could be orienting the students toward locating equations and plugging in appropriate numbers.

3.4.3 Retrospective Interviews

A year after the video recorded session, I interviewed each of the three students about the signal plot problem, their group work, and other types of tasks assigned to them in their engineering courses. The three students agreed this was a pretty typical homework session. Aurora remembered, "I think it was a fairly typical session for us. It was just come together, work on the problem in a collaborative way, have each person read it, have an idea of how they would do it, and just kind of compare of what everyone thought." Chloe and Sophia also agreed with this assessment.

When asked if all three students had the same goals and strategies for doing homework together, the students agreed they had similar objectives for the session. Aurora said, "I would definitely say we have the same goals, I mean, to finish the

problem and get it done and understand it." Chloe agreed, "All of us just wanted to get it done or get a good grade on it. That kind of typical thing." Sophia admitted, "I honestly can't answer that because I don't remember what I was thinking at the time but it's possible that some of us were more like, I just want to get it done."

Without prompting, Aurora also shared her thoughts on the problem assigned, "I don't think there's really much to learn from this actual problem. One, because (the professor) had already done it really in class, and this one it didn't really make you think very much which was annoying. I guess the only really part to learn was the actual MATLAB part."

During the knowledge construction episode, Chloe was the one who made the bid for sense-making. She was supported by Sophia, who added her own questions about the content. Aurora attempted to find a numerical answer but not an explanation to answer her group mate's questions. The interviews help explain the different ways these students typically worked through the problems. Aurora reported "For me, I tend to go a little bit faster and then go back later and try and understand it more and see what I did and how this works." Chloe, on the other hand, reported she and Sophia "would want to get the concepts more than Aurora" and at a different point reported, "When Sophia and I work together, we'll try to figure out, not just get an answer down, but figure out the concept of things." In this session, we did see attempts by Chloe and Sophia to try and understand the concepts but that discussion was limited by a group decision to wait for more information to be delivered by the professor. Yet, when asked about how she approaches the different tasks she is assigned to do, Chloe responded "Not a huge fan of book problems in general… that comes down to figuring out what equation you need, which

often is just guess and check. ‘Oh, I have these variables and equations. Well, these two equations have all those variables but I don't know which one to use.’ So you kind of try one, and it doesn't work try the other.” The process she describes is very similar to the process she, Sophia, and Aurora followed in the signal plot homework session. They established what variables they needed to solve for and started searching for equations to give them the answer.

3.5 Discussion

This study examined a mechanical engineering homework session of students solving a homework problem from their control systems class. The study looked at whether the students oriented their discourse towards task production or knowledge construction. We found students predominantly oriented towards task production. Yet, there was an episode where students made a bid for knowledge construction, but the context did not cue them shift their cognitive work toward making sense of the meaning of variables. Retrospective interviews confirmed students were oriented towards completing the homework, and group dynamics might have played into the dominant goals of the homework session.

It was surprising that the discourse of the homework session was so dominated by task production. The retrospective interviews and the course structure may give us insight to why this happened. The goal of this homework problem is to examine the input and output signals of a first order system. The values the problem asks for are what an expert in control systems would examine to understand the system before designing a controller to achieve the desired output. The way the problem is phrased does not ask the students to observe the signal, it asks them for a list of values. Yet their approach to the problem is

to use equations. There are four possible explanations that may help account for why the focus of the homework sessions seemed restricted to this frame.

First, the course emphasized a mathematical procedural form of problem solving. Aurora reported in her interview, “he (the professor) literally walked you through the steps but didn’t conceptually explain how to do this.” Sophia also reported, “class is a little spelled out, which makes it very easy to get a good grade…So in that sense, it’s not a great class if that makes sense, cause it’s not necessarily applied.” If this is what was constantly expected of the students, it should be no surprise that their attempt to figure out how to find an answer begins with looking for an equation in the notes.

Second, students’ approach to the homework problem was also constrained by the resources prescribed for use in the control systems course. The lecture notes were highly procedural, and there was not a suggested textbook for the course. These three students chose to do this homework with only the materials provided to them by the course, so they had only past lecture notes to help them with this problem. There are, of course, a multitude of online resources the students could have used. Students who participated in a related study in another course used the Internet frequently during their homework session. This group chose to stick to the materials provided in the course. Future research could explore how students make choices about when to consult online resources or textbooks not specifically suggested by the instructor.

Third, the retrospective interviews confirm the students were oriented towards getting their homework done. Both Chloe and Aurora admitted to that being the case. We also see evidence of the students framing the homework session as searching for

equations (Lee et al., 2013) and making calculations instead of making sense of the input and output plots.

Fourth, while Chloe and Sophia said that they usually liked to try and make sense of the problems they were solving, Aurora admitted to figuring out the problems and going back later and studying from them. When Chloe made a bid for sense making, Aurora's responses to her involved giving her equations from the notes, which had the result of squashing her bid and attempting to move on with the homework session. Overall, the flow of the homework session seemed to be dictated by Aurora. Chloe reported noticing that social dynamic while reading the transcript of the homework session and recalling feelings of frustration during the actual session. Despite Chloe and Sophia's intentions to sense make about the control system plots in the homework assignment, sociocultural norms and positioning among the three students may have contributed to a heavily task oriented session.

3.6 Conclusions

This study analyzed a single homework session of students solving problems assigned from a control systems class. During most of the homework session the students were engaged in task production, simply trying to complete the problem. The only exception was a series of bids to try and understand the difference between three variables. The students do not activate epistemological resources to sense-make about what the question is asking and how they might come to an answer. Students may have been cued by the structure of the course to search for a procedure to solve the problem rather than sense-make about the signals. Their retrospective interviews confirm they

were oriented toward completing the task, and social dynamics may have played a factor during the homework session.

This study is limited in that it is a single case study of only three participants. Yet, our development of a novel methodological approach of coding for task production and knowledge construction paired with retrospective interviews provided insight to the dynamics of the homework session. Unfortunately, the students did not engage in sense-making to construct knowledge about control systems. More groups of students solving different types of problems need to be studied to better understand how students develop conceptual knowledge during homework sessions. This study also shows the influence of epistemological framing on students' ability to problem solve and make sense of concepts (Hammer, Elby, Scherr, & Redish, 2005). More research needs to be done on the influence that cues from professors and course structure have on students' epistemological framing.

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Chapter 4: Opportunities for Knowledge Construction in a Fluid Mechanics Homework Session

4.1 Introduction

The previous chapter reported on a study that examined one homework session from a control systems course. I found the students primarily were engaged in getting the task done rather than having conversations to make sense of the content or build knowledge. In the one instance where students were trying to make sense of the content, they struggled because they were trying to find equations and make calculations instead of describing the frequency signals. For that study, I developed a systematic way of examining homework sessions using transcripts from the homework sessions and retrospective interviews. Yet, the data did not include any significant episodes of knowledge construction, and therefore it did not allow us to understand how students build knowledge through discourse during homework sessions or how and when students have knowledge construction conversations. The first study also was a single homework session. Further analysis needs to be done on different domains of engineering, types of course structure, form of homework problem, and groups of students.

To continue refining our understanding of the dynamics of undergraduate mechanical engineering homework sessions, in this chapter I report on a study that examines five homework sessions from a fluid mechanics course. This study seeks to answer the questions:

1) What does it look like when students engage in sense-making discourse during mechanical engineering homework sessions?
2) What are the triggers of episodes of sense-making during homework sessions?
3) How often do students shift to sense-making during problem set sessions?

4.2 Literature Review

My work examines engineering science courses. These engineering courses, such as control systems, fluid mechanics, and thermodynamics, use mathematics and physics as the backbone of reasoning and problem solving processes. Little work has been done in engineering education research to examine how student-to-student discourse builds knowledge in these subjects. I therefore turn to studies on learning mathematics and science knowledge to help guide us in our analysis.

In the previous chapter, I used an established coding scheme used by Koretsky and Nolen (2014), and created by Volet and Vauras (2013), paired with retrospective interviews to examine the discourse of students during homework sessions. In this study, my aim is to expand the use of this method to examine more groups of students in a different engineering domains and extend the work one step further to understand (a) how episodes of knowledge construction are triggered and (b) how students engage in sense-making discourse. I am particularly interested in students' development of conceptual ideas and understandings about phenomena. While the development of mathematical problem solving processes is important to engineering, I am more concerned with students' understanding of what equations 'say' (Gupta & Elby, 2011) that I am with students' ability to use them. Other studies have examined mathematical problem solving in engineering (Gainsburg, 2015).

My work in understanding the development of conceptual ideas or students making sense through discourse is inspired by work in science education. Engle and Conant (2002) and Berland and Reiser (2009) each provide examples of ways students develop scientific ideas through developing explanations and arguments. I want to

understand how undergraduate engineering students might develop ideas of their own through discourse during homework sessions. My analysis will first examine homework sessions by identifying utterances of task production and knowledge construction (Koretsky & Nolen, 2014; Volet & Vauras, 2013). I will then unpack the discourse of episodes of task production, bids for knowledge construction, and episodes of knowledge construction guided by research in science education on sense-making, explanations, and disciplinary engagement. Finally, I will use retrospective interviews with the participants to further unpack the findings.

4.2.1 Sense-making

To understand how students construct knowledge through discourse, I look to literature on mathematics and science sense-making. Science education researchers such as Michaels, O'Connor, and Resnick (2008) and Berland and Reiser (2009) call for students to participate in the discourse of science to build knowledge by constructing explanations and arguments. This view of science learning assumes that students bring with them intellectual resources which they can activate to explain and argue when instructors provide compelling phenomena to consider (Hammer, Elby, Scherr, & Redish, 2005). When forming explanations and arguments, students have to activate their everyday and scientific resources and articulate how they make sense of phenomena and disciplinary ideas. In this study, I seek to understand whether and how undergraduate engineering students use homework sessions as opportunities to make sense and construct knowledge of fluid mechanics.

At the undergraduate level, Gupta and Elby (2011), Hammer (1994), and Lising and Elby (2005) have examined students who believe that to solve physics problems they

must exclusively use equations and math instead of also drawing upon common sense reasoning. These studies found students had the resources for common sense reasoning but their *epistemological framing* of the work they were doing in physics, or way they thought knowledge should be used in a particular situation, was to identify correct equations. Physics education researchers assert that it would be more productive for students to frame problem solving sessions as opportunities for sense-making. Gupta and Elby (2011) describe sense-making in mathematics as "looking for meaning and coherence within the mathematical formalism itself and between math and the system it describes (p. 2465)." Similarly, Brock and Taber (2017) define making sense as "the formation or modification of a conceptual structure in which concepts are related in a coherent system that may be applied to a range of contexts" (p. 160). In this study, I am looking for instances when students are attempting to make connections between equations and physical scenarios or reason about the underlying processes of a phenomenon.

4.4.2 Productive Disciplinary Engagement

Engle and Conant's (2002) seminal study of productive disciplinary engagement provides another useful framework for investigating sense-making in engineering science courses; this framework accounts for how students become highly engaged in authentic disciplinary work. Engle and Conant examine two groups of students working on a project about orca whales. As part of this project, students get into an argument about classifying the orca as a whale or a dolphin. Engle and Conant identify this episode as one of productive disciplinary engagement (PDE). They argue the students are *engaged* because of the number of weeks the argument lasts and, despite a multi-week pause to the

project, the way the students re-engage in the argument again and again, providing new evidence each time. They argue the students are *disciplinarily* engaged by the ways they are bringing new evidence to the argument and using discipline-specific (in this case, biology) language. Finally, they claim students are *productive* because they are intellectually progressing and making headway toward solving the dilemma at the center of their argument. Engle and Conant's construct dissects student behaviors into markers of productive, disciplinary work. When analyzing the argument, Engle and Conant (2002), and later Engle (2011), listed markers of the students' engagement, disciplinary engagement, and productive disciplinary engagement.

Indicators of *Engagement* The students working on the orca project were filmed throughout their work on classification, before, during, and after the classification argument. Engle and Conant (2002) examined the video records for markers of engagement throughout all these work sessions. During episodes where the topic of orca classification came up, students overlapped when speaking, made contributions to the conversation that built off of one another, and were more responsive to each other's comments. The students' bodies also showed their interest through emotional displays, body positioning, and eye gaze. The researchers also noticed more students were participating in the activity and less were engaged in off topic tasks than in other pieces of orca project work that did not deal with classification.

Indicators of *Disciplinary Engagement* The students in the orca whale classroom were disciplinarily engaged with the material because they labored to make claims supported by evidence in the same way that biological scientists would. During the argument, students made claims about whale and dolphin anatomy, debated scientists'

use of classification terms, and even questioned the credibility of different sources. The students' questions and competing explanations were structurally similar to those made by scientists in the discipline. Student discourse also included words such as "because" and "so" and questions such as "why?" and "how do you know that?"

Indicators of *Productive* Disciplinary Engagement The analysis conducted by Engle and Conant (2002) revealed that students were productive because their arguments and claims became more sophisticated over the six weeks the students worked on the orca project. The students' research caused them to reject some of their original assumptions, raise new disciplinary questions, and make connections between pieces of data. The students moved from simply posing "individual ideas to comparing, challenging, and synthesizing them (p. 167)." Students searched for additional evidence to bring into the debate to aid their side of the classification argument and produced more knowledge. Through their work, they were progressing towards the canonically correct answer.

When analyzing homework session video in this study of engineering learning, I used these markers of productive disciplinary engagement to find episodes of sense-making and knowledge construction.

4.3 Methods

4.3.1 Participants

The students in the fluid mechanics course were third-year mechanical, environmental, and biomedical engineering students. I made a recruitment announcement during class time to explain that I was conducting a study of homework sessions, and students volunteered to participate in the study. Groups of students who typically worked together were identified from the consenting population. I started with students I knew

from my research laboratory, prior courses for which I had been a teaching assistant, or prior research, assuming they would be more motivated to coordinate on scheduling and more at ease during data collection. Students were contacted by e-mail to determine if their group was working together on the problem set and, if so, the time and location of their work. Three groups participated in the research. They differed in behavior, focus, and discourse patterns.

Group 1: Emma & Rachel Emma and Rachel were mechanical engineers on the same varsity athletic team and worked closely together. They consistently were very focused on their work and worked purposely to finish it in one session. They were quieter than the other groups, at time working silently next to each other until they checked an answer or needed help from the other person.

Group 2: James, Matthew, & Sabrina James, Matthew, and Sabrina were biomedical engineers. Their session was full of laughter, funny voices, jokes, sarcastic comments, and off-topic remarks about current social events. Despite this lighthearted nature of the session, they worked to get the problem set done as it was due a few hours after the session ended.

Group 3: Ken, Grace, & Janelle Ken, Grace, and Janelle were mechanical engineering students. Their session contained the most discourse back and forth about the work and had much more of a collaborative nature. While they didn't always work through problems at the same pace, they checked answers, equations, and use of constants with each other as they did their work. Grace and Janelle, when working on the same problem, reasoned out loud to each other about the steps they were deciding to take. Ken had more exposure to the disciplinary content than the other students in this session.

He worked in a fluid mechanics laboratory over the summer and taught himself pieces of fluid mechanics before this class in order to do his job in the laboratory.

4.3.2 Course Context

Fluid mechanics is a required course for a bachelor of science in mechanical, civil, environmental, and biomedical engineering. Students typically take this course in their third undergraduate year. The course is taught by faculty in the mechanical engineering department, and the section of the course involved in this research was one of four offered in the fall semester the study took place. The specific section was chosen for research because of student comments about the professor. Students in retrospective interviews in my previous study on control systems identified the problems assigned by this professor on quizzes and tests as the best kinds of questions they were asked during their undergraduate tenure. In class observations, I found the professor does not rely on a lecture-based pedagogy as it typically used in undergraduate STEM courses. Instead, in this fluid mechanics course, a typical session consists of the professor calling on the students to solve each step of an example problem on the board. In a 75-minute session, every student is called on at least once. The professor also uses hands-on activities to illustrate concepts such as filling balloons with water and poking holes in them, having students shoot him with a super soaker, and building rubber band cars.

The course had two 75-minute lectures a week. Students were assigned on average four problems of homework per class session. There was an in-class quiz, about fifteen minutes in length, once a week. If students scored poorly on these quizzes, they were allowed to re-do the problems to earn back points toward their grade. The quizzes

were intended for the professor to understand if the students comprehended the material rather than to make up a large portion of students' grades.

4.3.3 Tasks

Three different problem sets were worked on by the students while they were being video recorded. Two of these problem sets consisted of two textbook problems and two computational modeling problems devised by the professor. The third consisted of three book problems. The modeling problems asked students to create numerical and visual models of flows using spreadsheet software (Microsoft Excel). Quite of a few of the students had little experience using Excel and the problems were frustrating and difficult for them. Textbook problems were problems found at the end of the chapter in the book that typically required the use of equations and calculations to find an answer. I will describe two of these problems in detail along with related data later in the chapter.

4.3.4 Data Collection

During the video recorded sessions, students worked together on their homework assignment due the following class period. The problems included in the data set were a convenience sample; I simply recorded all the problems the students decided to tackle on the dates they gathered collectively to do homework during the study period of two weeks. Some recorded sessions included all the problems in one assigned set from beginning to end, while other sessions were only one problem. The goal was to record at least one authentic working session for each group, in order to examine their discourse involving conceptual ideas. Students were recorded using a camcorder with a lavalier microphone and audio recorder. Homework sessions were recorded in each group's venue of choice. They chose common spaces in the mechanical engineering department

and engineering school open to other students. Table 4.1 shows the entire data corpus of homework sessions.

Table 4.1: Group Homework Sessions Recorded

Group		
Group 1: Emma & Rachel, Mechanical Engineers	Problem Set 21: 2 book problems, 2 modeling problems	1 hour, 10 minutes
	Problem Set 22: 2 book problems, 2 modeling problems	1 hour, 30 minutes
Group 2: James, Matthew & Sabrina, Biomedical Engineers	Problem Set 21: 2 book problems, 2 modeling Problems	1 hour
Group 3: Ken, Grace, & Janelle	Problem Set 21: 2 book problems, 2 modeling problems Problem Set 22: 2 book problems, 2 modeling problems	1 hour, 10 minutes
	Problem Set 23: 3 book problems	2 hours

Students were asked to participate in retrospective interviews four months after the recorded sessions, at the end of the school year. Each participant in the homework sessions was individually e-mailed with a request to participate in an interview. Five of the eight participants agreed to an interview. Four were recorded in a small conference room on campus and the fifth was recorded over the WebEx conferencing platform. Table 4.2 details the interview data corpus.

Table 4.2: Retrospective Interviews

Name	Group	Major	Interview Length
Emma	1	Mechanical Engineering	1 hour 25 minutes
Sabrina	2	Biomedical Engineering	1 hour 38 minutes
Janelle	3	Mechanical Engineering	1 hour 13 minutes
Ken	3	Mechanical Engineering	1 hour 58 minutes
Grace	3	Mechanical Engineering	1 hour 30 minutes

4.3.5 Data Analysis

To understand how students are engaging in sense-making during their homework sessions, I first coded all five homework sessions to identify sections of *task production* or *knowledge construction*. To begin this process, I transcribed each homework session using video recordings and back-up audio recordings. Relevant gestures such as pointing or arm movements were added to the transcript. Portions of off-topic talk were not fully transcribed but noted as off topic in the transcript. These transcripts were imported into a spreadsheet. Homework sessions were coded line by line, using the above and below utterances for context (Pearce, 2007), as either task production, knowledge construction, or off-topic (Koretsky & Nolen, 2014; Volet & Vauras, 2013)(Table 4.3). *Task production* is talk focused on accomplishing a procedural task such as manipulating variables, computing mathematical operations, or comparing answers. An utterance is coded as task production if the goal of the statement is to move forward in the task. *Knowledge construction* is talk focused on making meaning, such as relating physical quantities to variables and equations. An utterance is coded as knowledge construction if the goal is to reason or make sense of equations or phenomena. In some cases, especially in Group 2, statements of knowledge construction were uttered by a student but not taken up by their group members. I refer to these as *bids* for knowledge construction. These were coded as lines of knowledge construction because the intent of the utterance was to make sense of the material instead of moving forward in the task.

Table 4.3: Homework Session Coding Scheme

Code	Definition from Koretsky & Nolen	Example
Task Production	Cognitive talk oriented at the completion of the set work that was prescribed by	Alex: Hmm, do you think we'll be working backwards from outlet to inlet? Cause

	the instructor	we don't know the velocity once it starts flowing through the thing right?
Knowledge Construction	Cognitive talk directed at making meaning, trying to build connections between ideas and understanding, and answering how and why questions	Ken: That makes sense cause we made the assumption it was zero at the bottom of that. Well, at least I did. (Bid) James: Well, we could, to make sure that it also makes sense.
Off-Topic	Talk unrelated to the engineering task	Janelle: I also have to go actually…

The addition of computer-based modeling tasks as part of the homework, instead of just paper-based mathematical problems, shifted the definitions of some of the categories in the coding scheme. Modeling is creating a representation, in this case both a numerical and visual of a physical system. Using the homework session video data, I had to determine what knowledge construction and sense-making conversations around computer-based modeling included, so I looked for instances where students were making meaning from the models. For example, in the following two episodes Emma, James and Matthew are talking about creating a model of a streamline of water with a source (analogous to turning on a water tap) and a sink (analogous to a drain). These models were numerically input as a matrix, and then once the initial conditions were input and the matrix values were computed the computer would produce a visual plot in color. The following utterance is early in the second homework session when Emma was asked to combine previously made models of a source and a sink together.

> Emma: So free stream is - what would happen if I just added a sink to this? You know what I'm saying? Like if I just - so this is my free stream and sink plot, and

if I copy pasted my source matrix and just added it. Like I want to know what would happen?

Emma is reasoning what will happen if she combines her previously made models of a source and a sink, if the two previous coded matrices would work together. This could be task production, as she is talking about steps of a putting pieces of information together. Yet, she is trying to make sense of how the models work. If they work separately, they should be able to work together. Ultimately, this was coded as knowledge construction because her tone and utterance suggest more of an intent to make sense of how the models work than an intent to operate on them.

The following episode occurs after James and Matthew have plotted their visual representations and are examining them and trying to understand what the representations really mean.

1 James: Wait, also, this is just like this way of plotting. It is totally conceptually twisted because the slopes are not actually where the water's going to flow.

2 Matthew: No, it has everything to do with the color.

3 James: Yeah, so, like the slopes aren't where the water's going to flow.

4 Matthew: It's the derivative of the slope. That's the speed of the…

5 James: Wait, I want to actually figure this out.

6 James: So the water doesn't flow down hill, the water flows only in the direction of equal height. It flows in the directions of equal height on this chart.

This episode was coded as knowledge construction because the students are trying to make sense of the representations they just created. James' statement in line 5, "Wait, I want to actually figure this out," clearly shows the orientation of the conversation.

I worked with another engineering education graduate researcher to establish inter-rater reliability for the coding scheme. After going through the code definitions and examples, the second rater coded 20% of Group 3's first session as a training set. The results were compared and discussed to find agreement. The second rater then coded 20% of lines from each of the five homework session beginning at a random place in the transcript of her choosing. 92% of the codes were matching. Most of the disagreements (80%) were about whether a line was off topic or task production. This disparity was typically over utterances students made about the course, the tools they were using (Microsoft Excel or computers), or jokes about progressing through the task. We dubbed these "fringe" utterances because while they were not completely off-topic, they weren't oriented to completing the task or constructing knowledge either. Between the five homework sessions, 80 codes out of a total of 3363 (2%) were changed.

Next, smaller portions of the transcript coded as knowledge construction were analyzed to understand how students were making-sense of the engineering concepts and how these episodes where triggered. Episodes of homework sessions were analyzed using discourse analysis (Goodwin, 1990), including gestures and intonation. Scans of students' homework were examined with transcripts to understand the fluid mechanics concepts and problem solving steps students took to complete the problem. In one case, my research group solved the homework problem step-by-step with portions of the transcript to understand the discussion the students had with each step of the problem. This process revealed each student's conceptual understandings, and how those understandings changed over the course of the homework session.

Finally, I concluded thematic analysis of the interview transcripts to triangulate (Merriam, 1998) and validate findings from the homework session. I examined responses to specific questions about the videotaped session including group dynamics and the nature of the assigned problem. I also examined students' thoughts on developing knowledge in engineering and looked for epistemological resources for learning engineering.

4.4 Findings

The findings are presented in four sections. First, I will present the results of coding the homework session discourse for knowledge construction and task production. Second, I will examine smaller episodes of knowledge construction. Third, I will provide a narrative analysis of an exceptionally long episode of sense-making where students are in disagreement about how to use Bernoulli's equation to solve a problem. Lastly, I'll examine the retrospective interviews to further unpack how students experienced the recorded homework sessions.

4.4.1 Fluid Mechanics Homework Sessions

The proportion of group homework time spent on task production versus knowledge construction varied by problem set and group. Group 1 had the fewest instances of knowledge construction, with no exchanges of knowledge construction in their first homework session and only seven lines in their second. Group 2 had six bids for knowledge construction, three that were not taken up by the group and three that started a short sense-making exchange. These bids were mostly made by James but went unanswered by the others in his group. In their first session, Group 3 had one longer conversation and a few shorter conversations of knowledge construction. In the second

session, there were many episodes of knowledge construction (between 3 and 33 utterances, average 13.5 utterances) and one 15-minute knowledge construction argument (131 utterances). This episode will be analyzed more in detail later in the paper.

Table 4.4: Homework Session Coding Results

Group	Problems Solved by Students	Duration of Homework Session (minutes)	Task Production (Utterances)	Knowledge Construction (Utterances)	Episodes of Knowledge Construction
Group 1: Emma & Rachel	Session 1: 2 book problems, 2 modeling problems	68	571	0	0
	Session 2: 2 modeling problems	87	496	7	1
Group 2: James, Matthew, & Sabrina	2 book problems, 2 modeling problems	53	523	20	3
Group 3: Ken, Grace, & Janelle	Session 1: 3 modeling problems, 2 book problems	72	539	77	4
	Session 2: 1 book problem	135	741	355	17

Task Production Instances of task production were focused on moving forward in the homework problem or getting the problem done. Examples of this include asking or telling a group member the next step of the problem, comparing answers, or uttering a mathematical operation out loud. When students were explaining an approach to solve the problem, their utterances were not coded as task production but knowledge construction. To illustrate the nature of task production discourse, below I share two episodes, one from Emma's group and one from Janelle's.

6.11 For a certain incompressible flow field it is suggested that the velocity components are given by the equations

$$u = 2xy \;\; v = -x^2 y \;\; w = 0$$

Is this a physically possible flow field? Explain.

Figure 4.1: Problem Solved by Groups 1 & 2

The following episode occurred during the first recorded problem solving session with Emma and Rachel. After finishing the modeling problem, they are just starting a book problem (Figure 4.1).

1 Emma: Okay, how do we draw a picture for this?

2 Rachel: Um, I don't think…

3 Emma: So we can assume incompressible, inviscid…

4 Rachel: Inviscid – what else?

5 Emma: Gravity's constant downward.

6 Rachel: Well, what's the other option? (head tilt and rolls her eyes)

7 Rachel: Is this (pause) physically… (pause) Okay. So we're just going to plug it into…

8 Emma: The definitions that we got…right? So, we did in class. You said that U is d…ah, what's it called again? What's the symbol?

9 Rachel: Phi

10 Emma: D phi. Yeah, dphi dy and v is negative dphi dx.

Here we see Emma and Rachel setting up a book problem. In class, the professor would have the students start each problem by drawing a picture and then naming all of the assumptions they could make. In lines 3 through 5 they are naming these common

assumptions together. In line 6, Rachel makes a sarcastic remark, responding to Emma's 'downward' comment, asking what other direction gravity could go. In lines 7 through 10 they begin to talk about what process they're going to use to solve the problem by identifying equations to use. This is a typical task production exchange. In the case of Emma and Rachel, they didn't typically go step by step with each other and usually would only check in when they were confused.

The following episode is from the second homework session of Group 3, which focused on the book problem shown in Figure 4.2.

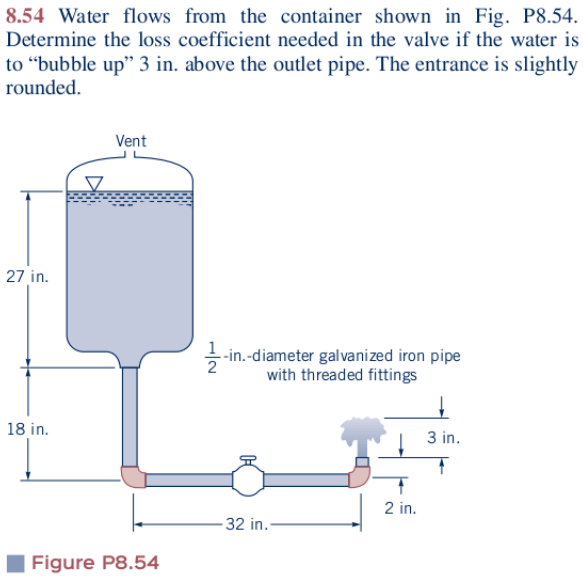

Figure 4.2: Water Tank Problem Solved by Group 3

The problem asks students to find the loss coefficient, K, needed in the valve if the water is only going to spring up three inches. The first step the students take in finding K is to determine the velocity of the water as it exits the pipe. The following excerpt is from early in their problem solving process.

1 Ken: Is that what they're asking for?

2 Grace: They're asking for the loss coefficient-

3 Janelle: Yeah.

4 Grace: -of the valve.

5 Ken: Yeah. Okay – oh of the valve?

6 Janelle: Yeah, I don't think…

7 Ken: Not everything?

8 Grace and Janelle: No.

9 Grace: Well, cause we – I think we would know the coefficient for the other things.

10 Janelle: And I think that's like the K value but I guess I'm just trying to figure out how to like use it in the equation. Whereas F over LD equals two plus (pause) the friction factor.

This conversation shows the students gauging what the problem is asking them to do. They establish they need to find the loss coefficient of the valve (Lines 5 and 6) and not the entire system of pipe (Lines 7 & 8). Janelle begins to search for an equation that includes the K value.

Bids for Knowledge Construction Sometimes students would pose a question to the group to sense make about a concept or an equation but none of the group members would join them to pursue that question. These instances are referred to as a *bid*, and were coded as knowledge construction because students were attempting to engage their peers in a sense-making conversation. This happened four times during Group 2's homework session. The following is an example of a discourse pattern that occurred in their homework session dynamics: task production talk focused on mathematical operations, followed by a bid for knowledge construction, and a rejection of that bid by a

group member. The problem the students were working on is shown in Figure 4.1. James begins working on the problem by thinking out loud the steps he thinks they need to take to solve the problem.

1 James: Oh, is it all we need to do? So we know that these (pointing to his note book) are equal. We just want to be able to say that (pause) um (pause) d, d squared psi over dx, dy is equal to, um, the opposite of - or is equal to d squared psi over dy, dx. And we get those by these (points to notebook) two things.

2 Matthew: So we have to take…

3 James: So we differentiate u with respect to x.

4 Matthew: Ooohh yes, yeah.

5 James: And then v with respect to y. Cause he showed that on the board right? I didn't write it down now.

6 Matthew: I have that.

7 James: So we don't even have to calculate psi necessarily.

8 Matthew: No, we just have to do the same.

9 James: Well, we could to make sure that it also makes sense.

10 Matthew: Or we could just take the teacher's word for it.

11 James: It looks like it is going to be…

James starts by proposing some initial steps they should take to solve the problem (lines 1, 3, and 5). Matthew agrees with his proposal. James then realizes they already have the tools from class to solve the problem and don't have to do further equation finding. James (Line 9) makes a bid that they make sense of the information they're using from the class notes. Matthew rejects his bid to make sense of it and calls from them to

move on with their task production of the rest of the problem. Of the four bids for knowledge construction and the short episode, James led in making these bids and constructing knowledge out loud.

Knowledge Construction Overall, Group 3 had significantly more instances of knowledge construction than the other two groups. The following exchange is from their first video recorded session. Here, they were asked to pick any shape and model the fluid flow around that shape. Grace, Janelle, and Ken chose a triangle. During the exchange, they are pointing to the following sketch on Janelle's paper (Figure 4.3).

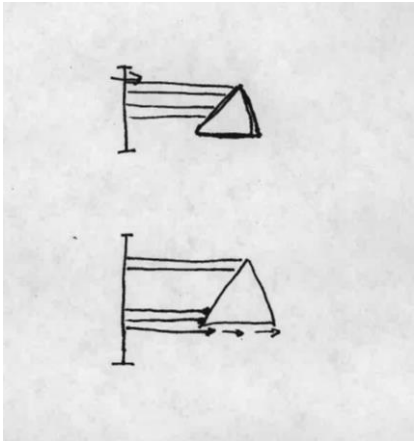

Figure 4.3: Reproduction of sketches from Janelle's homework

1 Ken: So at the bottom of the triangle, that corner, we can say that's a stagnation point. But as you go up along it, it's just going to be (points to her paper), it will still be some in the x and y cause it's at a slant. It will be less in the – but it will still be moving.

2 Janelle: I remember him saying in class that you know with the bugs and the car. Like, how you start with some air and then you're carrying it all the way through. Like, when you start, or when you arrive somewhere you carry, like, there's still air from like the place you left. Do you remember when he said that?

3 Ken: Yeah, as friction you carry it with you.

4 Janelle: Yeah, but doesn't that mean that at that point then the velocity is zero? And they were stagnation points here, because he talked about how the air hits this place, then it stays there until you arrive at your destination. So if it doesn't move up, it has to mean that the velocity at this point was zero.

5 Ken: Yeah, it's just one streamline vector. There's another one on top of that that might go up, or like there, and the way you drew this it's like this, is the bottom of a huge like parabola or circle.

6 Janelle: But you said that it's just when the lines are perpendicular they end up with a zero point.

7 Janelle: Well, the lines are perpendicular at the end of a zero point all along that perpendicular.

8 Janelle: Uuuhhh, okay, um…

9 Ken: Let's see.

In this episode, Ken and Janelle are trying to make sense of how to model fluid flow around a triangle. More specifically, they are trying to decide if just the bottom point of the triangle or the whole side is a stagnation point (Line 1)(Figure 4.3, bottom). Janelle brings up an example the professor talked about in class about the way bugs carried by air interact with the windshield of a car (Lines 2 and 4) and uses this example to figure out how a streamline will hit the side of a triangle. Ken seems to be translating her reasoning about the car into disciplinary language (Lines 3 and 5) and helps her figure out how multiple streamlines would interact with the surface. Janelle brings up an

earlier comment Ken made about lines perpendicular to the surface that end at zero (Line 6 and 7).

In this episode, we see Janelle bringing in evidence from class about how to think about streamlines interacting with a slanted surface. She and Ken reason together about how this model can be used to understand how a streamline will interact with a triangle and if the velocity will go to zero because of a stagnation point.

4.4.2 An Episode of Sense-Making

Examining all five homework sessions, there was one episode that stood out as particularly different in the nature of talk between the students. I noticed a difference in the students' talk while sitting next to them during the recording of the homework session. Suddenly, they were using their arms to make gestures, looking at each other while conversing instead of looking down at their notebooks or computers, and using a stronger tone when speaking. It was unlike any of the other seven previous homework sessions I'd attended. Analyzing their discourse, I found that the session consisted of knowledge construction for 15 minutes.

In this section, I will provide a narrative analysis of how students' sense-making conversation was disciplinary and productive to developing their understanding about fluid mechanics. But first, I'll summarize the context and main events of the episode. During this episode the students are working on the textbook problem in Figure 4.2. It asks students to consider a tank of water emptying into a pipe with valve.

Grace and Janelle are working together on this problem. They start by trying to understand the variables in this problem they haven't used before such as H (head loss), F (friction factor), and K (loss coefficient), and how the quantities of velocity, acceleration,

and pressure relate to this problem. Ken has been working independently on the problem but is answering their questions about headloss and the use of Bernoulli's equation. Table 4.5 summarizes the episode.

Table 4.5: Line by Line Description of the Argument

Line Numbers	Summary of Transcript
1-13	Janelle doesn't agree with Ken's answer for the exit velocity. She explains that she thinks his value is too big, and something might be wrong with his calculations or assumptions.
14-19	Grace and Janelle reason why Ken hasn't accounted for friction in his equations.
20-27	Janelle introduces a projectile motion analogy and they discuss energy equations.
28-41	Ken explains his process of solving for the velocity.
42-66	They return to the projectile motion example and discuss why Ken's method doesn't account for friction.
67-69	Janelle argues Ken is not using the right form of Bernoulli's.
70-79	Janelle argues why friction needs to be accounted for and Ken explains why there's no need to think about friction
80-92	They return to arguing about the form of Bernoulli's.
93-95	They agree to disagree because the argument does not appear to be approaching a resolution.
96-99	Janelle consults the textbook.
100-130	Janelle find a different way of solving for the velocity, which is the same way Ken did the problem. They pinpoint how they believe they misunderstood each other.

The episode of sense-making begins when Ken declares that the pressure at the outlet of the tube system is zero and announces that using that information, he found the velocity of the water exiting the tube is 48.15 inches per second.

1 Ken: The pressure of the outlet's zero, eeehhh!!!

2 Grace: The pressure at the outlet's zero?

3 Ken: 'Cause it's open to atmosphere.

4 Janelle: I don't know about that.

5 Ken: But it is going 48.15 inches per second.

6 Janelle: 48...

7 Ken: Point one five inches per second.

8 Janelle: And it's only going three inches?

9 Ken: Well, I found out from the outlet to that height. Both pressures are the same, the difference in height and the velocity at the top of the like water stream is pretty much zero cause that's like aaahhh (arm motion), and it falls back down, so I found out what the velocity exiting the pipe is.

10 Janelle: It can't be that fast because you're losing something to energy. But also if you were going that fast and only went three inches, like, I don't know, it would be like… 'Cause like you're saying the flow is going for less than a second. I mean not less than a second, 'cause I feel like forty eight inches per second is really fast, and like, the water would have to be dropping a lot faster than it's going. And also I feel like if you use projectile motion, if you're like exiting that fast like you'll do something like that (makes motion with finger). You don't just like crash after three inches.

Ken, solving for the velocity exiting the pipes, says because he found the pressure at the outlet is zero, he is able to calculate the velocity to be 48.15 inches per second. Janelle doubts both his assumption that the pressure is zero, and his value for the velocity. He explains that the pressure right at the exit as well as the water at the top of the spout are both at atmospheric pressure, which they are setting as their zero pressure value. Since the velocity at the top of the stream is zero, he's able to solve for the output velocity. His velocity value doesn't make intuitive sense to Janelle, and she proposes an explanation for why Ken's answer isn't correct. In Line 10, she turns toward thinking about a ball going at Ken's proposed velocity to try to reason why this value doesn't

make sense. She thinks an object (whether that be a droplet of water or a ball) going a 48.15 inches per second would not travel only three inches in the air but make a larger parabola. Finding errors in another student's thinking or equation is a common practice for this and other homework groups I observed. The students' conversation continues with all the students trying to understand Ken's calculated value for velocity.

11 Ken: Divide by twelve, that's…

12 Grace: Maybe that's…

13 Ken: Four feet per second?

14 Grace: Maybe that's what's supposed to be if there was no loss of friction. You haven't accounted for that right?

15 Ken: I mean, I don't have to. I know that the pressure at the outlet's zero, and the pressure at the top of the stream is zero, and there's the only thing that matters is the velocity being transferred as like-

16 Janelle: You're using Bernoulli's equation without friction, just not formally using it. But that's like what you're saying right now.

17 Ken: With the air?

Grace reasons that Ken's velocity value is wrong because he hasn't accounted for friction in the pipes and that's the reason his velocity is too high. He attempts to explain that he is only looking at the water after it has exited the pipe, when it's going through the air. Janelle picks up on Grace's reasoning about lack of friction and claims Ken is using Bernoulli's equation incorrectly (he's not). She continues to make her argument about something being wrong with the equations he's using. But she's not just talking

about the symbols in the equations; she's reasoning about how these numbers represent the behavior of the system in real life. These two don't equate in her head.

18 Janelle: No, cause you're saying that since the density is the - wait what - since the pressure is the same and then you are using the change in height to find the final velocity. That's just like another way of using Bernoulli's equation. Cause like that's what Bernoulli's equation is. That's like pressure, velocity. But the thing is Bernoulli's - unless you're accounting for the loss in friction, because there is some loss in friction here, then you can't -

19 Ken: But even with the loss of friction going through the pipe it's still going to leave with some velocity to be able to reach three inches.

20 Janelle: Yeah, but it's not going to be that velocity. Because okay, so if you have something that's going, like exiting at 48 inches per second, it won't just go up three inches. Because even think of a projectile motion but you're, like, kicking an initial velocity of 48 inches per second, it's not just going to do like bloop. It will be like waaaaaaaaa. You know? Just like if it's not water. Just something that you're initially kicking at 48 inches. Especially if you're kicking straight up, like 48 inches per second. That's a lot of initial velocity.

Janelle understands Ken's description and reasons he's using Bernoulli's equation but insists that this method does not account for the loss in speed of the water as it goes through the pipes. Ken is trying to communicate to both Grace and Janelle that he's only looking at the water after it's exited the pipe; therefore his equations take into account that energy lost due to friction. Janelle continues to argue that this velocity is too high. She goes back to thinking about a ball's projectile motion to illustrate her point,

explaining to her group members that if a ball were kicked at 48 inches per second it wouldn't go three inches high ("bloop") but create a high arc in the air ("waaaaaaa").

At this point, I call readers' attention to three things. First, Janelle has a strong intuition the number Ken found for the velocity is too high. She illustrates why she has this feeling by talking about a ball being kicked at 48 inches per second and explaining how its height would be more than three inches. Second, Janelle and Grace have reasoned Ken's number is too high because his equations haven't accounted for energy loss due to friction between the pipes and the water. Third, Ken tries to explain to them he is only looking at the water after it exits the pipe so he can use Bernoulli's correctly. Neither of the two women seem to understand this part of Ken's thinking and procedure.

The argument continues for nine more minutes, at which point they agree that neither of their arguments is convincing the other one and they need to move forward with the problem. In these first twenty lines, and the following 110, we see high engagement and sense-making about disciplinary concepts.

Before the argument, Ken was working independently and Janelle and Grace were discussing the problems together. Their eyes were focused on their notebooks or computers. As this argument started, they were looking at each other, gesturing, and pointing at each other's notebooks. Their conversation pattern changed from short exchanges about one equation or variable to an 11-minute exchange. The tones of their voices changed from flat and unenthusiastic to passionate and dynamic.

While the argument originated in Janelle's sense that the velocity value was too high, the conversation became about how to properly model the system and the correct use of Bernoulli's equation. Creating simplified models of physical systems is a typical

engineering practice (Diefes-Dux, Moore, Zawojewski, Imbrie, & Follman, 2004). In the case of this problem, Ken decided to only look at a piece of the system to simplify the model so he could use Bernoulli's equation. At the point of this conversation in the homework session, Grace and Janelle are still figuring out the equations and process they are going to use. Their arguments are disciplinary because they contain reasoning about mathematical models of designed systems, and use evidence about other familiar physical systems to reason how this system behaves. Instead of just talking about how to do the problem, they reason about how physical systems can be modeled using mathematical equations and ensure the equations being used account for how the system really behaves. Through having this debate, they are building their knowledge on how to model fluid mechanics systems.

This episode is also unique in the way Janelle brings other pieces of knowledge into the discussion to help illustrate her ideas. She brings in the idea of thinking about a ball instead of a stream of water. This becomes a simple physics example, one students most likely saw in their high school or introductory college physics. The other group members take this idea up and use it to make arguments as well. At one point even Ken says "I want to run kinematics on thinking like a ball to see if it comes out roughly the same as like a sanity check" (Line 42).

This argument also stands out from other conversations during homework sessions because the students, especially Grace and Janelle, advance their understanding of fluid mechanics concepts. Throughout the episode, we see some confusion about how to use Bernoulli's equation. By the end of the episode, Janelle shows she understands how to solve for the velocity "Wait, no, you're – we should use projectile motion to

figure out the initial velocity but backwards. You don't look at it from like 'oh there's a pipe' you look it as something going three inches high and has like gravity pulling it downwards. So you're trying to find the initial velocity in the y direction."

Analysis of five homework sessions showed the majority of students engage in task production while solving homework problems. Instances of knowledge construction are triggered by a student making a bid to make-sense of the material, or in one case, a disagreement about the validity of a calculated value. After analyzing homework session, I examined retrospective interviews to support the findings.

4.3.3 Retrospective Interviews

In retrospective interviews, students discussed how typical the filmed sessions were, how they think about doing homework with other students, and how they thought they were learning in the filmed session. In this section I present the findings from the interviews by reviewing each group's thoughts on the videotaped sessions, their group dynamics, and their approach to homework problems in this fluid mechanics class as well as other engineering science homework.

Both Emma and Rachel expressed in the interviews that they felt so successful as fluid mechanics learners that they "hadn't been working together really on those problem sets because, to be honest, we both really understood fluids just from the in-class time, and were able to do the homeworks independently." Yet, Emma said in terms of how they worked together, the video recorded homework session was "very typical. We work really well together; that's usually how things go. We spent a ton of time doing lots of our assignments together." In this specific session, their objectives were mainly determined by the amount of other work they had to do. Emma reflected, "So it was definitely toward

the end of the semester. I think in general we were just like, we need to finish this so we can do other things." This class was different for her because she really understood everything that was going on in class, and by this point in the semester, had found success on exams and knew she knew the material. She described, "So for me this was a low stress class where I was really focused on do I know what's going on? Can I do these problems? And if not, like, what you know, how do I just fix that really quick because I know I've understood everything else?" In her interview, she shared that this deeply felt understanding of the material was not something she experienced in most courses. She was very confident in her knowledge of the material for this particular course. In the case of this class, Emma may have had more opportunities to make sense of the material during class time, and therefore we did not see many during the homework.

Sabrina, from Group 2, reported she and Matthew usually "do our homework together, but like by ourselves next to each other type thing… So like pretty typical." Upon reading the transcript of their homework session, she noticed James and Matthew were "going through the formulas and then James is speaking out loud the conceptual part of it because he does that." She explained that understanding the material conceptually was "his thing. So he can then on the exam derive the formulas," and "he was really helpful in explaining the conceptual parts to me" when they studied together for the first exam. When they do homework together, she said, "is kind of annoying cause we're like 'Good enough. We get it. Like next step.' But he will not move on until he conceptually understands."

The reflections that Grace, Ken, and Janelle shared in their retrospective interviews helped me to better understand their sense-making episode. Janelle reported on

how usual the homework session was, “I would say that for [fluid mechanics] that was pretty typical.” Grace said she “wanted to do (the homework) in a group because I just think I have a better grasp of what the problem is asking and what I’m reading and learning when I’m talking it through with a people.” Like Emma, Group 3 commented on the time pressure they felt, and Grace reported that “we were trying to (pause) complete the homework assignment cause, I remember at that point there was a lot going on and so it was like ‘Okay, if we work together, like, you know, we can understand for the final but also kind of just get it done. And we had like other stuff to do.” But Grace also reported wanting to understand the material. “I think our strategy was similar in the sense we were trying to figure out what was happening with the water spouting at the end of the tube and just how to understand what to do with that.”

Janelle reported that she, as well as her group members, wanted to understand the problem. “I know that with this one I just like wanted to understand the problem and like how things work.” When asked about her group members, she responded “I don’t think they just wanted to get it over with. I think they also wanted to understand, which is like why we got into the conversation in the first place. It’s because we were both like – all three of us wanted to understand what was going on and how it worked.”

What was surprising was each of the students in Group 3 brought up unsolicited – before seeing the transcript – that they had a debate while being filmed doing their homework. Grace recalled, “I think I remember having like a very heated conversation.” The conversation was also very memorable for Ken. He described the unique situation by saying “Janelle and I were talking about the same thing but we didn't know we were talking about the same thing. So we both thought we were talking about something

different and we thought the other one was wrong. Which in the end was very funny. I remember we were like 'oh my god you're kidding me!'" Janelle also recalled the session fondly. "I remember … We had a disagreement on how something was going and if that was reasonable. And it ended up being actually the same thing but just we were going about it differently. Yeah, no it was funny." It is possible that this session was more memorable for the students both because they were being filmed and because they had this disagreement.

4.5 Discussion

This study examined five homework sessions of students solving fluid mechanics homework problems. Each of the five sessions was coded for task production or knowledge construction. Across the five homework sessions, students were mostly engaged in task production. Episodes of knowledge construction were examined to understand what caused students to shift to sense-making conversations. Most of these shifts were because a student in the group asked a question or made a bid. One sense-making session stood out because of its length and the students' commitment to their claims about how to solve the problem. Retrospective interviews were analyzed to confirm the coding of the homework sessions and better understand students' views of the homework sessions.

Like the homework session studied in the previous chapter, most of these homework sessions were dominated by task production. Prior studies in engineering (Lee, McNeill, Douglas, Koro-Ljungberg, & Therriault, 2013) and physics education (Bing & Redish, 2009) suggest students mostly engage in calculations and procedural execution to solve assigned homework problems. It should be noted the modeling tasks

and first fluids problem (Figure 4.1) involve working only with mathematical abstractions, while the tank problem (Figure 4.2) asks for analysis of—and determination of a quantity for – a concrete physical system. There is almost definitely a connection between the type of problem or system students are asked to analyze, concrete or abstract, and the amount of task production and knowledge construction. In this study, the problems students solved were the assigned problems for that week and were not selected by the researcher. Future studies could control for problem type and explore this relationship more specifically.

Despite the sessions mostly dominated by task production, in interviews, although some students admitted their goal in these homework sessions was to get the homework done, other students, specifically James, Janelle, and Grace, expressed that they very much wanted to understand the material. In other words, they had a personal engineering epistemology that included conceptual understanding as an important part of engineering learning and their homework discourse seemed to be aligned with that epistemological stance.

4.5.1 Group Summaries

Emma and Rachel, the group with the highest amount of task production, reported already feeling confident about the material. Emma also reported that Rachel is not one to talk a lot. Emma and Rachel's sessions were also dominated by Excel modeling problems, something Emma described as frustrating. These problems seemed to include more task production discourse across the five sessions and three groups in general because students struggled with the software and needed to help each other through the process of creating the models. Emma explained that in other courses such as heat

transfer, homework sessions were a place she and Rachel needed to learn concepts, but she felt confident about her knowledge of fluid mechanics. One might conclude that the amount of task production indicates that Emma and Rachel have naïve views of what counts as engineering learning. However, data in the interview with Emma suggest the opposite, that she did have a well articulated sense of what engineering learning looked like. The dominance of task production talk could have been related to the problems they were given in the homework sessions. Both sessions include mostly talk about modeling problems as well as the problem in Figure 4.1. All these problems were much more abstract in nature than the tank problem. A different type of problem may have given them more opportunities to sense-make.

Group 2's homework session had more knowledge construction than Group 1, mostly led by James. The coding of the data shows he initiated four out of five bids or episodes of knowledge construction. Sabrina, in her interview, reported many times she and her classmates consider their discussion is "good enough" to get their homework done, but James persists in attempts to sense-make about the material. From this data, we postulate James has a sense-making epistemology like Michael (Danielak, Gupta, & Elby, 2014). Without him in the homework session, it's likely that Group 2 would have looked similar to Group 1.

Group 3 had the most instances of knowledge construction, considerably higher than any other group. Their disagreement also resulted them in making more complex explanations and arguments, having deeper conversations about the material. Similarly Koretsky and Nolen (2014), found groups engaged in disciplinary productive talk when there were instances of "productive friction" in groups. In retrospective interviews, both

Grace and Janelle explained when doing homework they wanted to understand the material. Grace was even more specific, saying she wanted to do the homework with other people because she believes it helps her learn better. Further analysis of the interviews revealed that both Grace and Janelle value discussing and explaining concepts to other people as a key mechanism for their engineering learning. Examining their discourse during the homework episodes, I found that they have very explicit knowledge construction discussions before they even started two problems (a modeling problem in session 1, the tank problem in session 2). These discussions seem centered around taking stock of the concepts discussed in lectures and given information of the problem and understanding them before picking a method to solve the problem. There seems to be an unspoken understanding about what they are doing together in these sessions to come to an understanding and build knowledge.

Literature from science education has suggested creating situations where students make claims or arguments with evidence. Studies have shown in these situations students make sense of phenomena while articulating their understandings (Berland & Reiser, 2008). In order to encourage student sense-making conversations, more engineering problems could be designed that asked students to make claims and explanations or debate with each other in classroom or recitation based discussions. Work in physics education has created tutorials that pose a description of a real life situation where students have to reason what is going on using conceptual knowledge (McDermott, 2001).

4.5.2 Shifts to Knowledge Construction

Three episodes of knowledge construction were presented in the data: Group 2's bid, Group 3's modeling problem, and Group 3's disagreement. Group 2's episode is a stated bid by one student to further make-sense of the method chosen to solve the problem. In this case, it is James' wanting to make sense of the material. In Group 3's modeling problem, the episode is initiated by a conversation before the presented episode between Grace and Janelle about how to begin modeling water going around the shape, and what equations and conditions they need to know to be able to model it. Here, the episode was initiated by taking stock of what they know and understand, and what they need to be able to do. Janelle and Grace had a similar conversation before the disagreement (9 episodes of knowledge construction, 126 utterances of knowledge construction). Lastly, Group 3's disagreement is initiated by Janelle's intuitive sense that the velocity value is too high, her understanding of how gravity applies in the situation, and her and Grace's understanding of how to use Bernoulli's equation. This was unique in that all other episodes seemed to be initiated by a student bid or conversation.

For James, Grace, and Janelle, their epistemologies seem to allow them to shift easily between task production and knowledge construction conversations, both through questions and conversations taking stock of the problem. In studies by Elby and Gupta (2011, 2005), interviewers are able to cue students stuck in thinking physics can only be done with equations to shift into using common sense to aid them in solving physics problems. Besides making shifts for understanding, there is also an evaluation of solutions, both by James when he's analyzing the results of a modeling task (in section 4.3.5) and Janelle when she's evaluating Ken's solution. This practice of stepping back

and asking ‘Does this solution make sense?’, was modeled by the professor of the fluid mechanics class. In her retrospective interview, Janelle also discussed being educated in engineering was “tuning your gut.” James, Grace, and Janelle have epistemologies that set the stage for cues in the environment to trigger sense-making conversations.

4.6 Conclusions

This study showed students were mostly working together to complete their homework instead of making-sense of concepts. Shifts to sense-making conversations were initiated by a question by a student to cue their peers to help them make sense of an equation, a physical system, or calculated results. However, the generalizability of this study’s findings are limited by the small number of cases analyzed. Yet, the results point to the need to reform the ways homework is presented and the types of problems assigned to students in engineering science courses to encourage more knowledge construction and less task production. Cues from professors could help change the way students epistemologically frame (Hammer, et al., 2005), or understand how they are supposed to use knowledge in a particular situation, their homework assignments. Research in science education points to the need for students to form explanations and arguments to better understand concepts (Berland & Reiser, 2008; Michaels, et al., 2008) and a study of students solving statics problems found students who produced more self-explanations were stronger problem solvers (Litzinger et al., 2010). Problems could be redesigned with a focus on explaining a students’ problem solving process instead of a single numerical answer or write an explanation of how they would analyze a particular system. I encourage the development of different types of homework problems and research in the ways students engage with these problems. Further research into epistemologies is also

important to understand why students take up problems and think about homework sessions. Engineering researchers should build on work in physics (Hammer, 1994; Lising & Elby, 2004) on personal epistemologies.

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Chapter 5: Mechanical Engineering Students' Epistemologies

5.1 Introduction

Research on the epistemologies of students in STEM disciplines has shown that how students think about knowledge and the processes through which it is developed and used affects their learning. For example, when physics students adopt an epistemological stance that considers physics as only a manipulation of equations, their ability to problem solve and make sense of phenomena and concepts is hindered (Hammer, 1994; Lising &Elby, 2004). Similarly, Schommer (1990, 1992) found students' epistemologies have effects on comprehension and learning in the physical sciences, mathematics, and the social sciences. This work demonstrates the importance of accounting for students' epistemologies in undergraduate math and science education. Because these two disciplines are tightly coupled with learning engineering, it seems likely that students' views on what counts as engineering knowledge and how that knowledge is developed also make a difference for engineering learning outcomes. Yet, engineering faculty and education researchers have limited information about how engineering students understand the nature and development of engineering knowledge.

Compared to research in math and science education, research on students' engineering epistemologies is scarce (Beddoes, Montfort, & Brown, 2017). In 2006, the Journal of Engineering Education named epistemology one of the five most important emerging research areas for the field (Steering Committee of the National Engineering Education Research Colloquies, 2006), yet there still seems to be confusion on how it should be examined. In a review of epistemology as discussed in engineering education editorials and meetings over a ten-year period, Beddoes and Schimpf (2015) found "four

distinctly different conceptualizations of epistemology" (p.6). Research on epistemologies, both to help clarify the concept and to identify its impact on learning, is needed in the field of engineering education research.

There are two aims to this chapter. The first purpose of this chapter is to report on a study that demonstrates the dynamic nature of student epistemologies in engineering science courses. Research on epistemologies has shown that while in one context a student may reveal a certain view of how to develop or use disciplinary knowledge, in a different situation, or even later in a single interview response, her epistemology may shift (Lising & Elby, 2005). The data analyzed for this study also revealed shifts within single interviews. In this study, I aim to highlight engineering students' many different epistemological resources, examine how these resources influence their approaches to learning, and show why it is important for engineering practitioners to pay attention to them.

The second purpose of this chapter is to give engineering students a voice in the evolving, multifaceted narrative about what counts as valuable engineering knowledge and how one can develop that knowledge. Engineering schools, departments, and practitioners are constantly measuring and evaluating student learning gains. Evaluations by the national accreditation body, ABET, ensure programs and courses include canonical as well as cutting-edge disciplinary content, and ask for evidence that students are learning it. Engineering educators study how students are learning conceptual knowledge (Nelson, et.al., 2017), design instruments to ensure that students are learning that conceptual knowledge (Vigeant, Prince, Nottis, Koretsky, & Ekstedt, 2016), measure their ability to design (Atman, Adams, Cardella, et.al, 2007), understand how students

learn professional skills (Walther, Miller, & Sochacka, 2017), and analyze how they work on teams (Menekse, Higashi, Schunn, & Baehr, 2017) and learn or do many other things. While some studies have interviewed students about their capstone design course (Lutz, Ekoniak, Paretti, & Smith-Orr, 2015), few have asked for their perspective on how they learn or have developed engineering science knowledge. While many stakeholders evaluate and study students, their own perceptions of and opinions on what counts as knowledge are rarely documented in learning outcomes data. As an engineering student for eleven years, I can attest to this. This chapter is to document, analyze, and understand what students view as important engineering knowledge and the strengths and weaknesses of the system intended to help them develop it.

I will begin with a review of studies of learners' epistemologies in science and engineering education and an outline of the theoretical framework for this study. Next, I will introduce my participants and describe my methods of data collection and analysis. Then I will share my findings on students' views of engineering knowledge and its development. Lastly, I'll discuss these results and the implications they have on engineering education research and teaching.

5.2 Literature Review

5.2.1 Models of Epistemology

Here I present three models of epistemology used by science and engineering education researchers. More comprehensive reviews can be found in Hofer and Pintrich (1997) and Gainsburg (2015).

Developmental model. Perry (1970) conducted the first experiments to measure students' epistemologies. According to his developmental stage-based model, as students

move through their undergraduate experience, they develop more sophisticated ideas about knowledge and, progress through the stages of dualism, multiplicity, relativism, and commitment within relativism. The model was criticized for being based on only men at an elite school, Harvard University. In response, Belenky (1986) interviewed 135 women both in and out of school. She presents five different perspectives on a developmental path: silence, received knowledge, subjective knowledge, procedural knowledge, and constructed knowledge. While Perry had focused on students' views of the nature of knowledge, Belenky focused on how students perceived the source of knowledge (Hofer & Pintrch, 1997).

Dimensional model. Schommer (1990, 1992) proposed a different kind of model based for students' epistemologies. His model posits on four dimensions: fixed ability, quick learning, simple knowledge, and certain knowledge. Students answered 63 questions and were placed on a spectrum for each dimension. For example, at one end of the spectrum for "quick learning" is the belief that learning happens quickly or not at all, and at the other end is the belief that learning happens gradually. In Schommer's model, where a student falls on the spectrum for each of these dimensions is their epistemology.

Personal epistemologies model. Hofer and Pintrich (1997) built off the above models, arguing that the stage model does not account for mechanisms between stages, and the dimension model is too restrictive by pigeon-holing individuals into only one dimension at a time. They proposed that epistemologies could be described as personal theories which fall under two categories, nature of knowledge and nature of knowing. Views of the nature of knowledge deal with its degree of *certainty* and *simplicity*. Views of the nature of knowing involve the *source* of knowledge and *justification* of knowing.

Hofer and Pintrich did not argue that students explicitly and intentionally develop personal theories of learning but rather that as students' epistemologies become more sophisticated, their ideas of learning are less like unrelated bits of knowledge and more like a coherent theory.

Epistemological resources model. Hammer, Elby, and others (2002, 2005) discuss epistemologies in terms of resources. *Resources* are little pieces of knowledge which students call upon to form a new idea or understanding. *Epistemological* resources are the bits of knowledge that students have about knowledge in a particular scenario. They are activated based on context and are not fixed or stable; they change as students continue through school to become more sophisticated beliefs (Hammer & Elby, 2002). Epistemological resources can be sorted into four categories: nature and sources of knowledge (e.g., knowledge is propagated stuff), epistemological activities (e.g., accumulation), epistemological forms (e.g., stories, facts), and epistemological stances (e.g., belief, doubting).

In summary, researchers interested in student epistemologies have moved from relying on a staged-based model to recognizing that learners' ideas about knowledge and learning vary by are context. The stage-based model is limiting because it presumes a students ideas about learning the same across all types of knowledge. It is also difficult to measure a student's movement through stages because to record significant changes, a student needs to be studied for an extensive period of time.

5.2.2 Studies of Students' Epistemologies

Science and engineering education researchers have studied students' epistemologies using all three epistemological models: stage-based, dimension-based,

and resources-based. Because the research participant context, the method of data collection, and the analytical model vary across previous studies, it is difficult to make significant connections between them and theorize as a field about how engineering students view, produce, and consume knowledge. It is clear more work needs to be done on epistemologies in engineering.

McNeill, Douglas, Koro-Ljunger, Therriault, and Krause (2016) did not examine *epistemologies* per se, but engineering students' *epistemic beliefs* about problem solving in engineering. Researchers analyzed think-aloud problem solving sessions and interviews with nine male material science engineering students in their junior and senior years of college They found students thought about problems either as classroom problems that were "closed-ended, contrived, and focused on mathematics" (p. 576), or real-world problems that were "complex, open-ended, and requiring the consideration of diverse criteria" (p.576). Students' problem solving methods were different depending on the type of problem. Students' also identified two things every good problem solver needs: resources and personal characteristics. Resources were things like textbooks and the internet as well as other people. Personal characteristics were things a student had such as a good conceptual understanding, intuition, and confidence. This work contributes a model of how students think about problem solving but does not examine whether students see themselves as developing engineering knowledge through problem solving. However, McNeill et al. found students' epistemic beliefs were context dependent, similar to the resources based model.

Gainsburg interviewed first-year through fourth-year students enrolled in courses that use mathematics to solve engineering problems (2015). Analyzing think-aloud

sessions as students worked on their homework, she categorized student epistemologies about the role of math in engineering problems. These categories were loosely based on Perry's developmental categories; starting on one end of the spectrum with the belief that problems should be solved using a procedure to find one right answer to, on the other end of the spectrum, understanding when math should be used to solve engineering problems and the methodology behind these mathematical techniques, before using them for modeling. While this work shows a trend in how fourth-year engineering students' epistemologies differ from those of first-year students, it does not shed light on the mechanisms that drive that trend.

David and Marshall (2017) investigated students' epistemologies using the resources model in the context of a project-based introductory engineering course and found that the students' epistemologies shifted from needing knowledge to come from an authority to being comfortable constructing their own knowledge. Although they examine a single pedagogy, project-based learning, their results suggest that when given opportunity through inquiry and case-based problems, students can shift their epistemologies.

Elby and collaborators have examined how students think about physics knowledge by examining students in undergraduate physics courses. They have built off the work by Hofer and Pintrich (1997) to examine epistemologies by examining student behavior in different contexts. Through an interview study, they find compelling evidence that the activation of certain epistemological resources affects opportunities to learn (Lising & Elby, 2005). For example, some students behave as if mathematical reasoning should be used above common-sense reasoning when solving physics

problems, and who therefore they do not see a link between mathematical equations and everyday reasoning (Gupta & Elby, 2011; Lising & Elby, 2005). These students begin their interviews with mathematical reasoning but then shift to common sense reasoning. The authors claim the students have the resources for sense-making about physics, but they aren't activated because of the students' epistemological stance toward the discipline.

Recently, Elby and collaborators have started analyzing undergraduate engineering students' understandings of engineering knowledge development. They examined how the epistemology of one student, Michael, was tied to his identity, and how the mismatch of that identity with his engineering peers made him question if he belonged in engineering (Danielak, Gupta, & Elby, 2014). Through classroom observations and interviews, the authors find that Michael has a deep commitment to sense-making, or making meaning of concepts and unpacking what a mathematical equation means in the physical world. During interviews, Michael expresses frustration that the educational system does not reward students for sense-making and that his classmates are unwilling to participate in sense-making with him. The authors argue that Michael's identity as a sense-maker marginalizes him in the school of engineering. This study offers a compelling narrative about why engineering practitioners should pay attention to students' epistemologies, but it does not explore in depth how pedagogy and problem types affect student epistemological resources.

Smith and colleagues (2014) leveraged Elby et al.'s approach to attending to learners' epistemologies in an interesting way. They asked undergraduate engineering

students to read and reflect on Elby's (1999) study examining how students would advise their peers to learn physics. Then they analyzed students' responses to the question:

> "In section IV, the author contends students are rewarded by rote learning. In what ways are physics students rewarded? Do you believe your engineering classes reward rote learning in a similar way? Support your position."

Student reflections indicated that they recognized conceptual learning as a better way to learn material but saw rote learning as being more frequently rewarded. Many cited time constraints as the reason why they didn't strive for conceptual understanding. This study is limited in that it only examined a single, written response from the students. Focused on differences between rote and conceptual learning, this short written artifact could not provide enough information to understand a student's full set of epistemological resources.

Taken as a whole, this body of work on student epistemologies in undergraduate physics and engineering courses shows student epistemologies interact with opportunities for knowledge development, and that results are context dependent. In my research, I intend to capture students' thoughts about how they develop engineering knowledge and what resources current students have for thinking about engineering knowledge and learning. My study draws on both the dimensions and resources models and does not intend to rank students' intellectual progress or use this work to develop a scale. There are multiple aspects to a student's views on engineering knowledge and its development. During the interviews conducted for my study, each student emphasized different subsets of those aspects. Across student views, there were no two students who had the same

ways of thinking about and developing knowledge. This study attempts to understand student epistemologies around the context of assigned tasks, first beginning with a task in a specific course, and using that as a comparison to broaden the discussion to other courses.

The study presented in this chapter builds upon prior studies of engineering epistemologies but attempts to fill in at least four gaps. First, while most studies in undergraduate engineering education, including those mentioned above, focus on men, the participants in this study were six women and one man. This predominantly female sample was not the result of an intentional sampling strategy, but because it occurred, it allows the study to focus on a population which usually is highlighted only in research that focuses on gender disparity in recruitment or retention. Second, this study contributes to the literature by its orientation toward out-of-class tasks and homework. While many studies of student tasks in engineering focus on cornerstone and capstone design experiences, this study primarily reports on learning experiences in engineering science courses, a focus of the middle years (Lord & Chen, 2014). Third, many of the above studies of engineering students focus on math, but this study made an explicit request of students to articulate their views of engineering knowledge more broadly. Finally, while the above studies make inferences about student engineering epistemologies from surveys or written responses, or from classroom or problem solving observations, this study asks them for their epistemological views directly during in-person interviews.

This study was guided by three research questions:

1) What do upper-level mechanical engineering students think counts as engineering knowledge?

2) How do upper-level mechanical engineering students think they develop that engineering knowledge?
3) What pedagogical choices by the instructor – both during class time and for out-of-class assignments – do students notice and regard as productive for their development of engineering knowledge?

5.3 Methods

5.3.1 Participants

The data set for this chapter consists of seven interviews conducted between 5 and 12 months after the end of an engineering science course (either control systems or fluid mechanics) in which the students were video recorded while doing homework. The participants consist of three female students in their fourth year of college and four students, three female and one male, in their third year of college. All are mechanical engineering students. Interviews ranged from 49 to 118 minutes and averaged 83 minutes.

Table 5.1: Participants

Name	*Interview Length*	*School Year*	*Course*
Chloe	49 minutes	4th year	Control Systems
Sophia	1 hour 40 minutes	4th year	Control Systems
Aurora	51 minutes	4th year	Control Systems
Emma	1 hour 25 minutes	3rd year	Fluid Mechanics
Grace	1 hour 30 minutes	3rd year	Fluid Mechanics
Ken	1 hour 58 minutes	3rd year	Fluid Mechanics
Janelle	1 hour 13 minutes	3rd year	Fluid Mechanics

All names are pseudonyms.

Sophia, Chloe, and Aurora were all juniors when they participated in the homework recordings and seniors a year later when they were interviewed. While all three had been doing homework together off and on throughout various courses, Chloe and Sophia had a close working relationship during their junior and senior years. At one

point in her interview, Sophia declared “I seriously wouldn’t have graduated without Chloe because we did so much together in terms of helping each other.” When they were interviewed, Chloe and Sophia were just finishing a course on engineering education where they had been reflecting on their undergraduate experience and studying educational theory.

Emma, Grace, Ken, and Janelle were all juniors when they participated in the homework sessions and were interviewed. Grace, Ken, and Janelle were video recorded during two homework sessions together. Emma worked with another participant who did not respond to interview requests. Both Emma and Janelle had experience teaching elementary school students engineering through an outreach program. When she was interviewed, Emma was also finishing a course the same engineering education course Chloe and Sophia had taken the previous year. The semester between the fluid mechanics course and their interviews, Ken and Grace both studied abroad at the same university. All four students have worked on research projects in different research groups on campus.

Table 5.2: GPA Range of Participants

Name	*GPA Range*
Chloe	3.7-4.0
Sophia	3.7-4.0
Aurora	3.3-3.7
Emma	3.0-3.3
Grace	3.7-4.0
Ken	3.3-3.7
Janelle	3.3-3.7

Table 5.2 shows self-reported GPA. The reported GPA for Chloe, Sophia and Aurora is their GPA after four years of undergraduate work. The other four students reported their GPA as of the middle of their fourth year of study. All of the students

interviewed averaged over a 3.0 GPA and were all well performing in the classes involved in this research.

5.3.2 Data Collection

I conducted one semi-structured interview with each of the seven participants. The interviews were part of a larger research program on undergraduates' approach to engineering science homework problems, and the original intent of the interview protocol was to elicit participants' perspectives on previously video recorded homework sessions, including their sense of how typical those session were for them. Each interview had two phases. The first phase, which lasted from 31 to 56 minutes, involved reviewing the problem students solved in the recorded homework session (from either fluid mechanics or control systems), discussing group dynamics, and reviewing and reacting to a transcript of the recorded session. The second phase, which lasted from 18 to 62 minutes, involved specific questions about how other academic tasks compared to the task shown in the video and more general questions requiring students to reflect on their engineering education. For the last four interviews, the second phase asked students directly:

- How do you know you learned something in engineering?
- How do you feel you've learned something in engineering
- How do you define engineering learning?

Each of the first three participants addressed these questions during follow-up prompts from the researcher in the second phase of their interview. Their responses were particularly interesting, and after preliminary analysis of those first three interviews, these questions were formally added to the protocol for the later four interviews.

I conducted all of the interviews. There were semi-structured, meaning that I had a list of questions to ask all participants, but I followed up their responses to those questions with different probes to dig for deeper meaning. When I asked students to generalize across their experience, they tended to reply with narrative accounts of memorable tasks and problems. The shared questions across all interviews are included in Appendix A.

5.3.3 Data Analysis

Analysis of the interview data proceeded in four rounds: (a) open coding focused on student descriptions of tasks, (b) open coding focused on how students used the word "learn," (c) structured coding with categories about what counts as engineering knowledge and how it develops, and (d) final refinement and tabulation of applied codes. Within each round, I coded data independently and then presented data and corresponding codes to my research team for confirmation or revision. Research team members included one professor of mechanical engineering and education, and three doctoral students with backgrounds in educational research and either engineering or science.

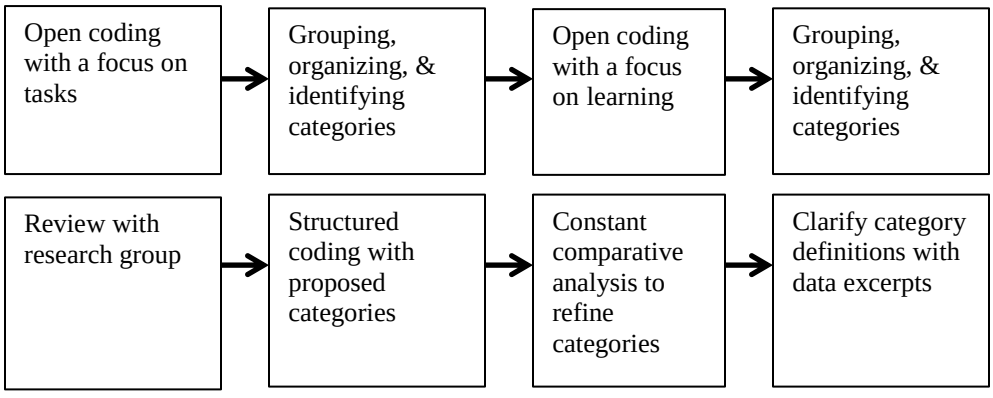

Figure 5.1: Development of Analysis and Coding

I began the first round by open coding all transcripts, underlining interesting statements and making notes in the margins. Because the larger research program was initially studying the characteristics of different types of outside-of-class tasks, this first pass through the data was mostly focused on students' descriptions of and reflections on the different types of tasks assigned to them, and resources students have for thinking about tasks. I looked at both phases of the interviews, so student comments pertained not only to fluid mechanics and control systems, but also any other engineering course they chose to mention. From these notes, I started grouping and organizing similar statements and making note of overall themes related to student descriptions of outside-of-class tasks. I looked for words and phrases repeated by multiple participants; for example, phrases such as "complex," "real-world," "applied," and "book problems" were repeated across interviews. I brought sections of the interview data to the research team to discuss potential themes.

The goal of the second round of open coding was to begin to identify themes related to students' personal engineering epistemologies. I went back to the transcripts and made new notes focused on how students used the word "learn" or "learning." I created lists for each student of instances where they directly said how they learn or phrases that characterized a story of a memorable learning experience. I also created diagrams to organize the ways they talked about different types of assignments and ways they were describing forming an understanding. I presented the research team with these diagrams along with possible categories and supporting quotes from the transcript text. We discussed the data and came up with proposed categories about what counts as engineering knowledge and how it develops. These are listed in the first column of

Tables 4 through 7. Using constant comparative analysis (Glaser & Strauss, 1967), I applied my notes from both rounds of open coding to refine the definitions for these categories.

Focusing on the word "learn" or "learning" during analysis was revealing, but its intended meaning within the interviews varied highly. I choose to use it in the interview protocol as a colloquial way to ask students about experiences of developing knowledge. During analysis, it became clear that when students used the word "learn" or "learning," its precise meaning depended on the context of that utterance. In many instances, students used the word to describe forming an understanding or mastery of a concept or process. For example, in Emma's response to the question 'How do you know you've learned something in engineering?' she responded "I know I learned something in class when I can do it on the homework myself…I know that I've learned something from the homework when I can recognize it on an exam" In other instances, students used the word "learn" to refer to being present for the delivery of information during a class lecture. For example, Ken describes how he "learned" material in a course he took studying abroad "I actually learned design for manufacturing at study abroad from just Powerpoints. It was great."

It could be confusing to use the word "learn" in a specific theoretical way in this paper's narrative while reporting on participants' varied uses of the term. Therefore, in this paper, I'll only use the word "learn" when I'm quoting students or summarizing their statements. In my narrative about the research findings, I'll use the phrases *develop knowledge* and *engineering knowledge* to reduce confusion.

In the third round of data analysis, I recoded all transcripts with the proposed categories about what counts as engineering knowledge and how it develops. I did this structured coding at the sentence level; I read each sentence uttered by the participant and noted whether it fit into one of the categories. In general, most sentences were tagged with only one code, but some had two. The most frequent reason for applying two codes was when a single sentence compared textbook problems to professor created problems. I made notes occasionally where themes appeared but no category existed. By the end of coding, two of these new themes appeared frequently enough to count as new categories of views on pedagogical choices by the instructor.

Finally, I conducted a fourth round of analysis on only the data excerpts that had been coded into one of the categories. After grouping the excerpts by category, I read through each slate of excerpts and threw out excerpts that did not fit or moved misplaced excerpts to the more appropriate category. The last step of this round was to tabulate how many students were represented in each category (Table 5.3 below).

5.4 Findings: Student views of engineering knowledge and how it develops

I will present findings in the order of my research questions. First, I report on three categories that characterize students' views of engineering knowledge. Second, I'll present ways students reported how they develop knowledge. Finally, I'll report pedagogical choices professors made for in-class and out-of-class tasks and activities. Results are not the result of direct questions about the topics listed but from analyzing narrative responses to questions about assigned tasks, courses, and the mechanical engineering program. A student not present in a category of results does not indicate they

do not have ideas on that topic or category, but that my interview questions did not cue them to respond with their ideas about that topic.

5.4.1 Engineering Knowledge

The first dimension revealed by the interview data is students' views of what counts as engineering knowledge. Data analysis revealed that the participants in this study conceive of three main kinds of knowledge they need as engineers: how to carry out a problem solving process, the relationship between physical quantities, and how to use a scientific construct to make technology work. Students showed understanding of the relationship between these three kinds of knowledge as well. For example, they discussed learning how to solve problems for their engineering science courses, but they expressed that were limitations to their knowledge of how to relate the scientific constructs they were learning in class to the real world. They shared their sense that as engineers, their jobs in the future will require them to solve complex problems with many undefined variables, and they need to develop a deeper intuition of how physical quantities relate to each other and knowledge of how to apply scientific concepts to make things work. Through reflections on their learning, they showed recognition that there is much interdependency among knowledge of problem solving procedures, knowledge of relationships between physical quantities, and knowledge of technological mechanisms. The study participants showed awareness that these are groups of knowledge cannot forever be practiced in isolation; they much be integrated with each other to solve real workplace problems.

In the sections below, I define each of three student views of engineering knowledge and illustrate each with representative student utterances.

Table 5.3: Views of Engineering Knowledge

	Chloe	Sophia	Aurora	Ken	Grace	Janelle	Emma
Knowing how to carry out a problem solving process	X	X	X	X	X	X	
Knowing about relationships between physical quantities			X	X			X
Knowing how to use a scientific construct to make a technology work				X	X		X

Knowing how to carry out a problem solving process Six out of the seven students made statements indicating that they view *knowing how to carry out a problem solving procedure* as an important part of engineering knowledge. In most cases, students described needing to know how to solve textbook problems. Grace though, discussed needing to solve problems both mathematically and using the design process. When asked how she would define engineering learning, Grace responded "I think it's all about processes… how to use processes to break down a problem and, you know, whether that process is literally a formula or is asking questions, like, you know, how can we make this better? And like methodically going through different ways we can make a certain product better." Other students put a similar emphasis on the importance of knowing how to solve a textbook problem. When describing this piece of knowledge, most discussed the many different types of problems given to them for certain classes and their varying difficulty that required them to use a process to come to an answer.

Aurora discussed the key thing she learned from her engineering science classes was the process of how to solve a problem, "you know reading the problem, taking a step back, what do you have? What don't you have? Then how do I analyze this? How do I fit it to a real world problem?" To learn the process, she explained, "you actually do it and someone shows you how to really look at it." Throughout her entire interview she repeatedly emphasized how important it was for her to learn the process. She described

the ways different professors taught problem solving by articulating all the steps and decisions when solving a problem.

Knowing about relationships between physical quantities Four of seven students also expressed the view that besides problem solving skills, engineering knowledge also includes intuition and understandings about *how physical quantities relate to each other*. For example, Ken said that to learn engineering means to have "understanding of how the world actually works in a physical sense." Similarly, Janelle said "I would say it's like getting a good intuition on how things work." She stated she thinks assigned mathematical problems are assigned to "give us a basic intuition, slash, understanding to how things work." While the assigned problems are heavily mathematized, she thinks what professors really want students to take away is a sense of how quantities relate to each other. She explained, "I don't think the numbers matter as much, although like, some people would disagree with me. Yeah, the math is important, but it's like if you, for instance, someone tells you that this thing is going at one hundred meters per second. And then you know that it's too fast because of the constraints, you don't have to know it's going at like 18.62. But like as long as you know that it's not like one hundred, and it's not one meter per second, I would say you're pretty good." Janelle believes these math problems serve the purpose of building up an understanding of physical quantities, so that when she and other engineers are asked to solve problems, they can make approximations using their trained intuition.

Knowing how to use a scientific construct to make a technology work Three of seven students' interview responses also revealed their sense that proficiency in engineering science includes that ability to *apply scientific knowledge to create things*.

Illustrating this view, Emma discussed one instance in fluids class where the professor had them build toy cars powered by a balloon expelling air; she interpreted this task as a sign that engineers apply their knowledge of fluids to make something work. “So with the balloon cars, I think that the goal of that at that point was we all understood that the air coming out was going to push the car forward. But the point was to emphasize how that actually happens and to get us to have - we had sort of like a mental model we could draw, a model on paper, but to actually be able to touch and manipulate what a physical model of that looked like. So to me that was the point of the balloon cars.” She explained that students had a sense of what an analysis looked like on paper but their professor used a simple building exercise to illustrate how their knowledge could be used to make something work.

Grace and Ken also discussed making connections between their coursework and seeing it in the world around them. When asked how she knows she has learned something in engineering, Grace began by saying “I think it’s usually when I see it around me.” She told a story to illustrate what she meant through an interaction with her father. “We were talking about like a hot pan on the stove and then like sticking it in the cold water and then my dad was like ‘That’s heat treatment.’ And I was like, ‘Oh yes, that is heat treatment. I learned about this in ME 25.’ ” She continues by talking about another experience she had with Ken. “Ken and I would just be out walking around and then we’d notice things. I think it was even just a pulley that we kind of talked about in physics way back when. I think those are the times when I realize I’ve learned something.”

Ken also talked about making connections between his courses and products in the world around him. “When you exit a class you should be able to look at whatever that class would be applied to (and) be able to understand what’s going on behind the scenes and have a general appreciation of how much time and effort really goes into it. And how much thinking and trial and error goes into it before you have a finished product or structure or whatever.”

5.4.2 Developing Knowledge

The second dimension revealed by the interview data is students’ views of how learners develop engineering knowledge. In other words, through what mechanisms does engineering learning happen? Throughout the interviews, students revealed – through both direct statements and stories about their education – six different ways they develop or see others develop engineering knowledge. Their views unpack the reductionist notion that engineering learning happens either through physical making or through doing mathematical problems. Students recognized those activities as central to knowledge development but described a number of other practices they use to develop their engineering knowledge.

In the sections below, I define each of the six student views of how engineering knowledge develops and illustrate each with representative student utterances.

Table 5.4: Views of Mechanisms for Developing Engineering Knowledge

	Chloe	Sophia	Aurora	Ken	Grace	Janelle	Emma
Doing problems				X	X	X	X
Doing physical making	X	X				X	X
Looking at models (completed problems)		X	X				
Listening and watching		X		X			

Discussing with or explaining to other people	X	X		X	X	X	X
Making mistakes			X	X	X	X	

The most surprising result is that six out of seven students identify discussing or explaining to other people as a way they develop knowledge. It is also important to point out no one student has exactly the same set of ideas about engineering knowledge development as another. Emma and Chloe and Ken and Janelle have similar sets, but they differ by one category each. There are no common "profiles" or "types" of learners we can pull out from Table 5.4. Each student is unique in the ways he or she views the development of engineering knowledge.

Doing problems Four of seven students identified doing problems as the best way they develop engineering knowledge. Most students discussed how the problem sets assigned for homework function to solidify the material they "learned" in class ("learned" in the sense of having been present during information delivery by an instructor). As Grace explained, "I use these (textbook) problems to practice for understanding the concepts. A lot of the time I don't fully get it until I'm like going through the examples with numbers and diagrams and then I can see where these concepts are applied." Janelle shares this view with Grace but adds that the level of challenge presented by a problem is important for knowledge development: "Doing problems that are challenging and that really make you stop and think, but you have to like think about for a few hours…Sometimes you take a break from it and then come back."

Ken also responded that "doing" problems is the way he learns engineering. When he studied abroad, regular homework assignments weren't given, so he sought out problems to solve in order to learn the material. "I learn by doing, so that's consistent. [In

the study abroad location] there was like lectures with no reinforcement…I had to dig up a lot of practice exams, or like practice problems, and things to do. And go through the theory like a little more, like in parallel to a problem, and see how it's applied." Ken needs the practice problems to build his understanding.

Physical making While all students acknowledged that doing mathematical problems helps to build engineering knowledge, a few described physically making and building things as the way they learn best. Chloe repeatedly expressed her preference for classes that included a building component, "I like that sort of hands on. You're actually building, you're doing something, learning. I feel that's when I learn the most." Emma also expresses how physically making solidifies concepts for her. "I think the feeling of learning it is when you are able to implement it successfully. So to me, I didn't learn proportional control in controls, I learned proportional control when [another professor] explained it to me, and I actually made my violin robot do that. I didn't learn about how electro magnets work in physics, I learned about them when I actually built a circuit that actually made an electro magnet and saw it switch. Like that, you know, that to me is like the feeling of learning, as opposed to, 'I can write these things down that I know, but I have no idea what they actually represent in real life.' "

Looking at completed problems While most students talked about building knowledge by doing problems, a few also expressed a view that they develop knowledge when they look at completed problems. Aurora and Sophia both described looking back at completed problems to sense-make about the material. Aurora talked about her learning process and how she uses homework problems to study. "I'll go back later and studying for tests or like even before a class if I didn't get something. I'll look back and

just be like, ‘What exactly was this and why are we doing this?’ And so once I can see like what I’ve done, and kind of laid it out, I have a better understanding of how the problem works. …I may not get it right away but when I go back and look at it and work through it myself, that's when I start making connections.” Sophia also said that after completing a particularly difficult problem, she goes back and uses it to sense-make: “Then from the problem, like oh, like after, I can study from this now that I've done it. And that's where the learning happened, more so then in the process of getting the answer.”

Listening and watching While most students identified “doing” as a key activity for knowledge development, two students still discussed “learning” from listening to lectures. Two of the students discussed content presented in class as “things we learned in class” while describing how they solved a particular assigned problem. Ken acknowledges listening to lectures about information helps him through exposure: “Class is good, I guess, for just like, for what class is useful - exposure and learning theoretically what to do.”

Ken also expressed a view that “real life examples from people” help him develop engineering knowledge. He talked at length about one professor who had been a vice president at an engineering company before coming to teach: “I like having professors of the practice, cause there’s more than just the technical stuff; there’s all this other crap you have to look out for.” He explains how listening to this professor’s stories about industry informed him about things “no one is ever formally taught in a classroom.” Ken revealed that students are thinking about their future careers in industry and want to learn as much as they can to help them be well-rounded employees.

Discussing with or explaining to other people On the flip side of benefitting from listening, Ken and Sophia and three other students also described talking as an important means to build understanding in engineering. In some cases, students talked about checking answers with other people. But five students expressed needing much more complex discourse than that, especially when homework problems were difficult. Six out of seven students explicitly mentioned engaging in oral explanation and argumentation with other students as a key part of engineering knowledge development.

Grace's descriptions of her methods of working on problem sets always included other people. She directly stated, "I just like, I think I have a better grasp of like what the problem is asking, and like what I'm reading and learning, when I'm talking through it with people." Even Ken confirms this in his interview stating, "I know Grace likes doing her homework with other people."

As shown above, Janelle stated that doing problems is how she learns, but both times she expressed that this is paired with explaining problems to or discussing problems with other people: "I learn doing problem sets and like actually — like I learn the most when I'm doing them on my own, and then after I do them on my own, then like, explaining it to people. But I think that's how most people - like explaining it to people is how most people learn." As we consider personal epistemologies, it's noteworthy that Janelle makes a point of stating she believes that's how most people learn.

Both Grace and Ken also discussed the importance of being able to explain engineering concepts to other non-engineers. One of the ways Grace knows she has some engineering knowledge is her ability to explain it: "My ideas of fully understanding something would be if I could explain it to my brother, who's in high school. And you

know he hasn't taken physics yet, so I guess my definition of fully understanding something would be if I could explain it to him."

The best illustration of student discourse contributing to the development of knowledge is the relationship between Sophia and Chloe. As Sophia described, "I had never met Chloe and then the beginning of junior year I went up to her and was like, 'Can we do homework together?' because she seems to do things early. And I was like okay, and then like both of our GPAs just went way up once we started doing homework together. At least I don't mind it because we were like, had someone to study with that I didn't feel ashamed to ask questions. I had someone to do homework with." She continues and ends by saying "I seriously wouldn't have graduated without Chloe because we did so much together in terms of helping each other." Sophia's story not only illustrates the essential role that sense-making with another person plays in her learning but also the importance of being able to ask questions without feeling ashamed.

Making mistakes Three students indicated that they saw making mistakes as productive for engineering knowledge development. Both Grace and Aurora mentioned that choosing the wrong equation or making a mathematical error in a problem solving process actually helped them learn the material better, once they discovered the mistake. Grace reflected, "I think even learning from the mistakes you've made and can see in front of you and like, can see like, okay, 'something's off' and then go back to the like, the readings to figure out why, or I don't know, fix it." Making mistakes seems to push her to go back to course materials to better understand the concepts.

Aurora described learning from mistakes as a mindset she enters during her problem solving sessions. "You just go with a different mentality, like, this isn't a step-

by-step thing, you just have to try multiple things. You're going to fail, or you're going to get the right answer, one or the other, and you go through that. Which I like, ‘cause you see what works and what doesn't work.” She views problem solving as an iterative process, and she learns how to solve different types of problems from using different methods.

Ken has learned from watching other engineers that engineering involves making mistakes. “Before I thought everything has to be right the first time, but then looking at other people who have a lot more learning than I do, or experience, a lot of it's trial and error.”

5.4.3 Pedagogical Choices – In Class

As students described their engineering learning, many made unsolicited comments about the pedagogical choices made by the professor and how these choices influenced the development of engineering knowledge. What stood out most in the data were participants remarks about the types of questions professors chose to ask for homework, quizzes, and exams. The way professors made course content available to students was also frequently discussed.

As students discussed their classroom experience, many discussed teaching methods that frustrated them as well as practices that really helped them learn. We focused analysis on their perceptions of pedagogical choices that were beneficial for their learning. The following section highlights the in-class practices that students noted as having helped their learning or that they wish happened more often. The subsequent section will focus on pedagogical choices related to out-of-class assignments.

Table 5.5: In-Class Pedagogical Choices Perceived by Students as Productive for Learning

	Chloe	Sophia	Aurora	Ken	Grace	Janelle	Emma
Practicing or making visible a problem solving strategy			X		X	X	X
Asking open-ended questions to *all* students and basing next steps on students' responses			X		X	X	
Starting with concrete examples and only bringing in theory at the point when it's helpful to solve that example				X			
Making visible the appearance of the same fundamental equation – but with variations – to model different scenarios, or different levels of abstraction of the same scenario			X	X		X	
Linking real world examples to material	X		X	X	X		X

Practicing or making visible a problem solving strategy A recurring theme in the data is the importance of mathematical problem solving to the students, and therefore it's no surprise that most students reported appreciating professors who focused on teaching problem-solving methods and strategies. Emma talked about her fluids professor in particular "He carried the theme of modeling and assumptions through all three all of the different types of things that we did (in fluids class). There was always that emphasis on 'How would you model this?' 'What assumptions were you making?' and 'Where do those assumptions start to break down?' " The professor made a problem-solving strategy clear by using it across different types of problems.

Grace, speaking of the same professor, agreed. "I think seeing it broken down every day in class, I think, made approaching a problem a little bit more easier because I was familiar with like, (pause) kind of like, you know, this is a big looming problem, and now I need to break it up. How do I break it up? So just seeing it just played out in class

every single day was really helpful." Not only was this strategy helpful for working on problems in the fluid mechanics class, but with other challenging problem sets as well.

Asking open-ended questions to ALL students and basing next steps on students' responses Students also reflected they appreciated when professors invited student participation by asking the students questions. Grace and Aurora both discuss one professor's method of involving students in the problem solving process and it helped their learning. Aurora wasn't in this professors' class but visited one day. She reported what she experienced. "I went to one of his lectures and it was -I really liked how he did this. It's not like a typical lecture format. You - everyone sits and he just starts doing a problem on the board and he calls each person one by one to ask them what's the next step, or how you would analyze this? And you just kind of got the fact that there are more variables than are actually given in the text book to think about, and he just makes - he would make you think about the whole system and how all of these equations and variables work together to actually solve this." Aurora's visit to the class opened her eyes to a larger complexity of problems than the given textbook problems to which she was accustomed.

Grace appreciated how the professor's style really made students pay attention. "I liked (the) professor's questions a lot, too. And I think they're really cool because like the whole class is going through one problem, and I like the way he kind of called on people to like, you know, work through it as a class. I think, just like, you know, there's really no way you could really not pay attention and get away with it. Right? And I think, like, kind of getting me to like, try to figure out. Okay, like this is one step, have a student answer this one step, what would the next step be? She noted that being asked to

participate in the class that way not only made her practice solving problems in class but also demonstrated how to distill larger, challenging problems into smaller pieces she was confident she could solve.

Starting with concrete example and only bringing in theory at the point when it's helpful to solve that example Ken noted one technique a professor used is to start with an example and introduce a concept when it was needed. The professor, he reported, "taught through examples, which I thought was really nice. There was very little theory and even when he built up the theory it was while solving an example, so that (snaps fingers) that was like my stuff."

Making visible the appearance of the same fundamental equation – but with variations – to model different scenarios, or different levels of abstraction of the same scenario Another teaching practice students appreciated was using the same fundamental concept or equation in many different examples that were slightly different from each other. With many students finding mathematical problem solving an important skill, they described needing repetitive practice both in and out of class. Janelle describes her experience doing this in class. "A lot of times it felt like we were doing the same thing over and over again, but that's actually just like what you need to do…So I really like these problems because they're just all really different and didn't seem like the same scenario. But you would just use the same equation, and that's what I think he (the professor) wanted us to get from it. It's just the simple equation that models something, and then you can use it for different scenarios as long as you just know how to set it up." Janelle describes her realization why the repetitiveness of seeing the same equation used in different scenarios was helpful to her understanding of the material.

Similarly, Ken described his experience with this teaching technique. “In class his (the professor’s) problems, we realized, some are from the book but he alters some things. And like as we got the basic down, then out of his - I think he added his own changes to it, which then make it a little harder. Also, I think it advanced our learning.” Ken described how small changes the professor made to problems increased the difficulty but also his learning of the material.

Linking real world examples to the material Students also appreciated when professors use or discuss real world examples of the concepts they were learning. Emma described her experience with a professor who was willing to examine real world scenarios. “I think that that professor’s sort of problem is pretty unique to him. I haven't encountered any other professors who are willing to sort of look at a real thing and just see where it goes. That's been, he's been my only experience with that. All my other classes have been very like, prescribed out of the book: these are the problems that we're going to do because I know the answer to them before I even start and can make sure I have a definitive answer for you.” Emma describes how she really appreciated one professor taking a risk in class to examine real world scenarios where there was no initial “definitive answer.”

Emma also described a lecture involving a real world example that she thought would be a great starting point for some experimentation. “He (the professor) had this great lecture that he gave about how sometimes insulation around a pipe actually like magnifies heat transfer, that there's a critical radius. So in, you know, some older houses, before they really understood this concept, the insulation is actually magnifying the heat loss from the pipes. And so that would have been a great experiment to actually

experimentally determine that radius." Emma described a lecture where the professor illustrated the use of the heat transfer concepts from class to real world applications.

Chloe described the type of quiz questions she had and the different kind of thinking it pushed her to do. "We had these quizzes where…he'd (the professor) say 'Oh, I have a house in New Hampshire' and he would draw a house on the board and say, 'talk about the heat transfer in my house.' And that would be your quiz. So you could take that one million different ways and you had ten minutes. It didn't matter if you talked about the radiation of the sun or not. It mattered what assumptions you made and it mattered how you thought about it, so having to actually think about like real world things rather than just figuring out a book problem." She described how the professor gave quizzes that pushed her to think about how to analyze real world situations and make assumptions to model a situation.

While a few students praised professors who brought a real world example into their classroom, many students expressed frustration there were not more real world connections in their courses. Many students expressed frustration at the lack of examples of real world situations where concepts were used or at the lack of physical models. Chloe expressed most students' feelings by speaking as if she were giving feedback to a professor "just bring it back more to the real world. I knew it was right beyond what we were doing where I could tell it was important, but I couldn't tell you why it was important."

5.4.4 Pedagogical Choices – Out-of-class

As shown in the above categories, solving mathematical problems with the guidance of professors during class time was important to students. For out-of-class time,

they affirmed that their assignments were typically dominated by problem sets, but they had nuanced views of how they learned from these tasks; they were clear that the form of learning depended on problem type. For example, students discussed the difference between problems in which they were asked to reproduce a process they had gone over during class and problems that challenged them by requiring them to make assumptions and decide what solution methods to use. Professors who discussed problem solving strategies and dissected complicated, real-world situations during class were naturally more likely to assign these types of problems for homework. Students, six of whom repeatedly expressed a desire to be pushed to solve these complicated problems, said they found it valuable when professors used complex and real world problems in their teaching and assigned out-of-class tasks. As Chloe summarized her feelings about how different tasks help her learn, she said "It definitely goes down to what type of questions they (the professors) ask." Table 5.6 shows qualities of out-of-class problems that students identified as being productive for developing their engineering knowledge.

Table 5.6: Pedagogical Choices for Out-of-class Assignments Perceived by Students as Productive for Learning

	Chloe	Sophia	Aurora	Ken	Grace	Janelle	Emma
Clear skill builders that isolate important procedural knowledge (i.e. intentionally chosen textbook problems)		X	X		X	X	X
Problems requiring the use of conceptual knowledge to determine what mathematical model shows the important relationship						X	
Problems that require the integration of different types of knowledge				X		X	X
Ill-structured problems that ask students to figure out and model the most salient features of a scenario	X	X	X			X	X

Clear skill builders that isolate important procedural knowledge (i.e. intentionally chosen textbook problems) The students expressed mixed views about the value of problems taken directly from a course textbook. Many described unsatisfactory experiences being asked to do complicated textbook problems that were not related to the information presented by the professor in class. Yet, if the textbook homework problems clearly matched up with the in-class material, students expressed a more positive attitude. Emma saw value in textbook questions "for like learning the tools that you're supposed to use and making sure you know how to use them." Similarly, Grace saw value in the problems to solidify her understanding, "I use these problems to practice for understanding the concepts. A lot of the time I don't fully get it until I'm like going through the examples with like numbers and diagrams, and then I can see where these concepts are applied." While not always their favorite problems, students see value in them for building skills and understanding concepts that would help them solve more complex problems they believe engineers solve.

Problems requiring the use of conceptual knowledge to determine what mathematical model shows the important relationship In contrast to textbook questions, which Janelle referred to as "plug and chug," students preferred questions that pushed them to think harder. As she explained, "There are other questions that I think are really cool when you, like, have to use part of the conceptual things to know which equations to use, and I think those ones are the gems, the really nice questions." One type of problem that was more complex asked students to use conceptual knowledge to determine their mathematical problem solving process to solve the problem.

Problems that require the integration of different types of knowledge

Students also expressed that they were pushed to learn more by problems requiring the coordination of multiple forms of knowledge. When asked which of the tasks assigned during her undergraduate education she most preferred, Emma responded, “Problems that are not prescribed and involve the integration of lots of different types of different knowledge.” Janelle elaborated on this idea by explaining why these questions are so important to her. She explained that when she is in the beginning chapters of a book she can look at “section part one, and then these are the questions for part one, and you know what equations you’re going to use with those questions. And it’s once you get later on that you’re like ‘oh, okay,’ now if you start it like mixing all the different sections together, but before then, you just like still kind of plug and chug.” She clearly noticed that problems from early book chapters use the equations from that chapter’s content and do not often ask students to integrate other types of knowledge.

Janelle contrasted this textbook limitation with how a professor created questions to challenge her beyond “plug and chug.” “I think it’s so when you make up your own questions it’s like you have - you’re thinking about how you can use everything you’ve seen in class to help. Like have everything together. But the thing is, also, they’re just harder, and that’s not everyone’s favorite thing.” These questions are deeply satisfying to Janelle, though. She shared that when she finishes them, she feels, “You come out and you're like ‘Oh my god, I am finally an engineer!’ ”

Ken described the problem sets written by one professor. “His are unique. I feel like he custom makes them every week. They’re nothing I’ve ever seen before and they actually require, a lot of times they require me to look up things on the internet and use

other materials." To Ken, these uniquely created problem sets ask him to use materials outside the given materials for class, but that teaches him how to use tables and other external sources used in problem solving. "I have to look at tons of data sheets and actually read them, which is good 'cause what I'm doing for my research now. I have to actually – I understand what I'm reading, and I know what to look for and know what everything says." These problems that ask him to use outside knowledge have taught him how to read and interpret these tables which feels like an authentic problem solving experience and has been useful to other work he's been asked to do outside the classroom.

Ill-structured problems that ask students to figure out and model the most salient features of a scenario Most students described the best kind of questions having a briefly described familiar, real world, scenario where they were asked to use their knowledge to analyze the situation. Emma explained how these types of problems asked you to think differently than textbook problems. "Textbook problems are designed to give you a certain answer, and so it – you, in solving them, you know that there's a set of assumptions you're supposed to come up with. A process you're supposed to follow and an answer you're supposed to arrive at." Emma described textbook problems as well-structured with certain conditions that make them work and usually a specific process the authors anticipate the learner following. As mentioned above, Emma saw these problems as good for skill building. She contrasted them with one specific ill-structured problem given to her by a certain professor. "Whereas when (a certain professor) puts questions up on the board, that's like the tree, and the wind made this motion, and like this happened. Everything that you're assuming, you have to come up with, and so you are

sort of controlling how you set up the problem and to what level you're going to be able to solve it by the parameters you come up with. So I can look at a tree and say 'I have no idea how fast that's moving, that's why I need to come up with.' I can say 'Yeah, it looks like two miles per hour.' Like you know, and use that in solving for something different." These ill-structured problems, based on real life scenarios, ask the students come up with the structure of the problem themselves by making assumptions. The student is challenged to think about all the different influences on the important quantities in the scenario and make decisions about what model will best account for them.

Chloe and Sophia identified similar problems as the best question they were ever asked. Sophia explained, "The best test question I ever had was there was a truck, and it was a refrigerated truck, and it was hot outside. And you had to figure out if something was melting in the truck or something like that. Like how fast or something." Sophia painted a picture of plausible real life situation that could be found outside on the street. She then described how she used content understandings developed in the course to solve the problem. "You were using conduction through the truck, and then you have the convection outside. And you had the conditions inside the truck, and you were applying these equations you had already learned so you learn the concepts. Like what is conduction? What is convection? Right? And you understand them. This was the final test question, so we had already did all of that a little bit, and you knew how to use the equations, and then you were applying it to something that was real. Real – like simulated – but real." Sophia explained how she felt this problem asked the student to have mastered the concepts of conduction and convection and be able to apply them to this

plausible scenario. She emphasized at the end how she felt this was a real application of her knowledge.

Chloe, as mentioned above, described her professor having the class analyze a house, and it was up to each student to choose how they wanted to analyze the house. As she explained, “You could take that one million different ways…It didn’t matter if you talked about the radiation of the sun or not. It mattered what assumptions you made and it mattered how you thought about it.”

Students felt having to analyze these scenarios pushed them in their ability to make assumptions, analyze, and choose the best way to model a real world system.

5.5 Discussion

This study interviewed seven mechanical engineering students about the types of tasks assigned to them in engineering courses. The interviews began by reviewing a problem students had completed during a filmed homework session and then asked students to compare that task to others assignments in the course and then other assignments in all engineering courses. Students identified three main groups of engineering knowledge: how to carry out a problem solving process, understanding the relationships between physical quantities, and knowing how to use a scientific construct to make a technology work. As the students talked about themselves as learners in the mechanical engineering department, they identified six different ways they perceive themselves to develop knowledge: doing problems, physical making, looking at completed problems, listening and consuming information, discussing with and explaining to other people, and making mistakes. Students also identified pedagogical

choices by the instructor both in class and through assigned out-of-class work that they believed best aided them in their learning.

Looking across Tables 4 through 7, we can identify epistemological patterns within individual student interviews and across the seven participants. For example, four of the seven students - Janelle, Ken, Auroa, and Sophia – centered their remarks around mathematical problem solving and engineering science type courses. Two students, Chloe and Emma, centered many of their comments around building and making. Though these patterns emerged, there is no way to definitively categorize different types of engineering learners with this data. Even if we look across participants who have experience in thinking and talking about learning in engineering (Chloe, Sophia, Janelle, and Emma), there is no common aspect across their responses that makes their ideas different or more sophisticated than students who have not participated in these conversations. The following conclusions are also not meant to be a comprehensive summary of a student's ideas about engineering learning; students took up my questions in different ways, and the interview can only capture the students' ideas at that moment, as cued by my questions. If a student didn't demonstrate an idea about engineering learning, it may be because my cues through interview questions did not activate resources on that idea or topic. The following sections discuss four of the significant ways these engineering students are currently thinking when working on their assigned tasks. I am highlighting them to encourage consideration of these four aspects in the future design of assigned tasks in engineering courses.

5.5.1 Problematizing the Privileged Place of Mathematical Problem Solving

Across this study's three dimensions – views of engineering knowledge, views of knowledge development, and views of productive pedagogical choices – one overarching pattern is students' awareness of the privileging of mathematical procedural competency. Students frequently discussed the act of completing problems and different types of problems assigned to develop mathematical problem solving skills. This result is consistent with expectations for two reasons. First, both courses at the focus of the interviews (fluid mechanics and control systems) were engineering science courses, courses where mathematical problem solving is taught and problem sets are frequently assigned. Second, most of the courses students had taken in engineering up to the time of the interview, especially for the four students who were third year students, are engineering science courses rather than engineering design courses.

It could be interpreted as troubling result that students who are about to enter the engineering workforce report a narrow focus on well-defined problem solving processes at the expense of experience solving different types of ill-structured problems they will most likely encounter in the workforce (Jonassen, 2014). Yet, it was promising that the students in my study were frustrated about this emphasis and had an understanding that solving only highly structured problems was not preparing them for their future engineering careers. Their view is consistent with research showing that even students who preform well on traditionally structured problems often perform poorly on measures of conceptual understanding (Sawrey, 1990; Streveler, Litzinger, Miller, & Steif, 2008). Yet their view differs from that of many faculty, who believe that teaching students to problem solve also teaches them conceptual knowledge (Sawrey, 1990). It is promising

that the students in this study have not also assimilated this belief and instead have a more complex, nuanced understanding of the types of problems they need to be able to solve. It is possible that these sophisticated understandings stem from their albeit limited exposure to at least a few ill-structured, open-ended assignments – which some of them reported experiencing in a few courses. Research in physics has shown when students are given ill-structured and open-ended challenges, their views shift from believing problem solving is applying one of a list of procedures to more expansive strategies (Ogilvie, 2009).

It is also promising that students recognize while "textbook" problems are clear skill builders that help them learn problem solving procedures, students recognize they need to be pushed further to be able to solve more complex, ill-defined problems.

5.5.2 Valuing Discussion and Oral Explanation

The most surprising result of the study was that six out of seven students identified discussing with other students or explaining to others – both peers and non-engineers – as an essential activity for their learning. Their view is supported by research on learning in several domains. In science education, when students engage in spoken arguments about the validity of competing explanations of phenomena, they develop more accurate understandings of those phenomena (Engle & Conant, 2002; Osborne, 2010). In math education, when students explicitly debate the choices they are making about mathematical procedures, they show sophisticated learning outcomes (Yackel & Cobb, 1996). In early childhood education, back-and-forth conversation between young children and adults is a mechanism for intellectual development (Romeo et al., 2018). Indeed, there is consensus in the K-12 education research and curriculum development

community that "sensemaking and scaffolded discussion, calling for particular forms of talk, are seen as the primary mechanism for promoting deep understanding of complex concepts and robust reasoning" (Michaels, O'Connor, & Resnick, 2007).

Despite the overwhelming view of the participants in my study and the consensus of K-12 education research, most undergraduate engineering as well as science and math courses continue to employ lecture based pedagogies (Kober, 2015) that do not encourage conversation among students. The findings of my study suggest that we need to provide more spaces for students to discuss, debate, and sense-make engineering knowledge. One example of this strategy integrated into the course is the Learning Assistant model developed at the University of Colorado, Boulder (Otero, Pollock, & Finkelstein, 2010). Undergraduate learning assistants hold recitation sessions once a week for students to discuss conceptual problems from the course. Learning assistants are trained not to solve problems for students but to ask good questions that drive discussion between students. Another option is in-class questions, often posed via "clicker" system, for which students discuss either in small groups or a large group how to solve a problem (Crouch & Mazur, 2001).

It is worth pondering why previous work on students' beliefs about engineering problem solving has not revealed how greatly students value talk as a learning activity. One reason that this finding emerges in this study, but not in previous work, could be that other researchers have not asked students to describe the sociocultural milieu in which they do their homework; they have only focused on homework and problem-solving as an individual endeavor. In my study, I purposely elicited information about the cultural context in which students do their homework. An additional factor may be the gender

makeup of my participants; six out of the seven participants were women, an atypical sample. The women may have been more likely to value talk, or to be willing to talk *about* talk, than the men who are more often included as engineering education research study participants. Ken in his interview described the difference he's experienced working with groups of men verses groups of women:

"If I work with a lot of guys it's everyone is definitely doing the wrong thing and no one really talks about problems until we're all sitting there like tearing our hair out. Like 'What is going on?' With girls they're a lot more easy. I mean it is still, they're still doing their own thing until it's a hard problem, but they more easily ask for help with like what's going on…They're more collaborative in that sense."

5.5.3 Two Roles

Another pattern that emerges when we look across all seven interviews is students' dynamic perspective on the main purpose of undergraduate engineering education. Throughout the interviews, five of the seven students spoke differently about developing the knowledge they need for their *current* role as an engineering student than they did about developing the knowledge they need for their *future* role as practicing engineer. In some sections of the interviews, they discussed things they perceived as contributing to success as an engineering student – being a good mathematical problem solver and understanding scientific concepts. Other times, they discussed knowledge they perceived themselves as needing to be a good practicing engineer – knowing for solving complex, ill-defined problems or creating a working prototype. The questions I asked the students focused on course related tasks, so any statements they made about knowledge for their future engineering careers were student initiated. However, students switched

perspectives without being aware. We see evidence here of two different *epistemological frames*. A frame is a sense of "what is going on here" (McCormick & Hammer, 2016) and an *epistemological frame* is a sense of how knowledge and learning should be used in a particular situation (Hammer, Elby, Scherr, & Redish, 2005). Being a good engineering student and preparing to be a good future engineer are two different senses of "what is going on" in an undergraduate engineering program. These two senses are informed by a variety of experiences students are having, not just in courses, but other aspects of professional preparation. These include internships, professional societies, and student organizations focused on building a product such as electric car teams or Engineers Without Borders.

Some of the students did not shift back and forth but predominantly discussed their development of knowledge in the frame of being a good engineering student. This finding mirrors progressions found in previous studies of epistemological development among engineering students. Stevens et.al. (2008, 2014) found as students moved from lower level courses to higher level courses, problems became less prescribed and more open-ended, and some students reported being uncomfortable with this shift. One student in particular felt particularly lost after starting senior design, because he had found success in mathematical problem solving and had to readapt to measures of success rooted in collaboration and ill-defined problem solving. Research by Gainsburg (2015) on engineering students' epistemologies related to math found "a personal commitment to the profession that shifts the view of learning from a matter of getting correct answers and satisfying instructors to understanding the concepts and procedures (p.149-150)." In my results, both the students who moved between the student and professional

engineering frame and those who were mostly in the professional engineering frame were eager to make this shift in their engineering work.

5.5.4 Tension between problem types

In this study, some students discuss how they see these mathematically based problems as productive for skill building but more complex, ill-defined problems will better prepare them for their careers as engineers. Other students express their strong dislike of textbook problems either because lack of preparation to solve these assigned problems during class time (Sophia) or the ”equation search” game students play in order to solve these types of problems (Chloe). Students are aware textbook type problems, a well-defined scenario in which students are solving a problem numerically to find a single answer, are not preparing them for their careers as practicing engineers. Evidence in Studies 1 and 2 show when students are solving these assigned problems, they are mostly engaged in task production activities instead of sense-making conversations, and their statements in retrospective interviews report they are mostly working on their homework to get it done (both reported on in this study and the two previous chapters). In the interviews, students express dissatisfaction with this learning system and would prefer more difficult, complex, ill-defined problems. One student, Janelle, even specifically identified problems that require the use of conceptual knowledge to determine what mathematical model to use. Students are aware they are mostly in “school world” but would prefer to inhabit “engineering world” more frequently in their education (Koretsky, Nolen, Gilbuena, Tierney, & Volet, 2014, Lorona, Nolen, & Koretsky, 2018). While none of the students specifically identify a lack of conceptual knowledge development, students recognize there is a deficiency in the system. Work needs to be

done by both engineering researchers and teachers to develop homework tasks that focus on developing conceptual knowledge.

5.6 Conclusions

This study showed upper-level mechanical engineering students' many different epistemological resources for developing engineering knowledge. However, the generalizability of this study's findings is limited by the small number of students interviewed. These students are high achieving and their reported learning experiences were at a highly selective institution with small class sizes. Yet, it's important to consider these high achieving students express how much more they could be learning if given the opportunity. The study is also unique because of the high number of women in the study. Further research needs to be done on engineering student epistemologies, specifically around engineering science conceptual knowledge. I encourage specific research examining the differences in epistemology of students in underrepresented groups or from different backgrounds. The findings of this study hopefully inspire more work into the ways students build knowledge through discussion.

This study examined interview data of seven mechanical engineering students discussing what counts as engineering knowledge, how they believe engineering knowledge develops, and pedagogical decisions by instructors that best helped them learn engineering. Students overwhelmingly called for more complex, ill-defined problem solving to prepare them for their future work as engineers. Students also shifted between different epistemological frames, considering both ways to develop knowledge for success in their courses and presumed ways to achieve success in their future engineering careers. Finally, six out of seven students also identified discussion with or explanation to

others as a way they learn engineering. We need to provide more opportunities for students to discuss engineering phenomena both in and outside of their courses.

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Appendix A: Interview Protocol

Could you describe how you normally work on a problem set/homework problem?
Describe how you normally work through a problem.
How frequently do you work with other people?
Can you describe the dynamics of working in groups?

Show them the problem(s) from the video
Here's the problem you worked on when I video taped you last year.
Tell me how you thought about working through this problem.
Tell me how this problem compares to other kinds of tasks you were asked to do in controls class?
How does this compare to the other kinds of tasks you did across all your engineering courses?
How did you approach those other kinds of tasks you mentioned?
How does this task compare to your vision of an ideal learning task in an engineering course?
How do you think these kinds of activities given to you as engineering learners?
Tell me about you as a learner in the ME department.

What I saw in the video was familiar to things I did in undergrad working with my peers. It struck me how collaborative you were in this homework session. How typical is the practice of how you worked together?
How do you and your friends/peers think/strategize about doing homework together?
What about labs? Is there a similar way of working on in-class or out of class labs?
What are your reflections about how you were learning in this session?

Show transcript from homework session
How do you feel about this task?
Talk about the dynamics of working together shown in this transcript/clip. Does
Do you think that you had the same goals and strategies for this problem set as the two people you were working with?

How do you know you learned something in engineering?
How do you feel you've learned something in engineering?
How do you define engineering learning?

6. Conclusions

6.1 Key Contributions of the Dissertation

The overall aim of dissertation is to shed light on the questions of whether, when, and how some undergraduate engineering students pursue opportunities for deep conceptual knowledge development in the engineering sciences. To address these questions, I have presented three empirical studies examining how students discussed and constructed conceptual knowledge during undergraduate mechanical engineering homework sessions.

Study 1 in a case study focused on one group of three female students and their work on a single problem from a control systems homework assignment. I found that the students mainly focused on getting the task done instead of using homework as an opportunity to make sense of the problem. The main contribution of this study is a methodological one: I developed a novel approach that combined *in situ* homework session data with retrospective interviews. I examined student-to-student discourse during a homework session in combination with one-on-one interviews in which I probed for students' recollections of the substance of their homework talk and used their own perspectives to confirm discourse analysis results.

Study 2 applies the methodology developed in Study 1 to a larger data set; it is a study of three different student groups and their work on fluid mechanics homework. I found that in most homework sessions students worked to complete the task with very few conversations to make meaning of concepts. This lack of sense-making conversations may contribute to students' struggles to reason systematically about the causal mechanisms that drive a phenomenon. The main contribution of this study is the finding

that shifts to sense-making were cued by a student's doubting another student's answer and by outright disagreement between students. The findings from Study 2 also emphasize the privileged place of procedurally rigid problem solving both in the students' expectations of what they are supposed to be doing during engineering homework sessions as well as the knowledge they believe they need to develop to be successful engineering graduates.

Looking across all six homework sessions in Studies 1 and 2, students were predominantly engaged in task production. While these studies highlighted the shifts into and bids for episodes of knowledge construction, most of the time during the observed homework sessions, students were not sense-making.

Study 3 is a qualitative descriptive study of upper-level mechanical engineering students' views of what counts as engineering knowledge and how that knowledge develops. Analysis of interviews with seven students revealed that students have substantial and complex ideas about what contributes to their development of engineering knowledge. Some students understand the privileged place of mathematical problem solving in engineering education, but they also believe that carrying out mathematical procedures only in service of completing well-defined problems will not completely prepare them for their jobs as engineers. Students expressed a need for more complex, real-world tasks to better prepare them for their future careers. Students also recognized the value in sense-making with peers and forming oral explanations about concepts. Yet, cues from professors or homework statements seem to contribute to students' epistemologically framing homework as only a task to complete. The main contribution

of Study 3 is the finding that students value discussing with and explaining to others – both classmates and non-engineers – as an essential activity for their learning.

6.2 Implications for Engineering Instruction and Future Research

I hope this dissertation speaks to not only engineering education researchers but also instructors of engineering science courses. Furthermore, in addition to contributing to the literature on conceptual knowledge in engineering and inspiring the development of new homework problems and tasks in engineering science courses, this dissertation also reveals the need for further research on engineering science homework sessions and engineering student epistemologies.

Results from Studies 2 and 3 suggest that students may benefit from having engineering educators who to pay attention to and help foster the growth of student engineering epistemologies. Study 2 showed that the students who revealed sense-making epistemologies in interviews were the same students who made bids for knowledge construction during group homework sessions. Study 3 showed that some students have complex, well-reasoned ideas about how they are learning engineering knowledge and what helps them to better develop that knowledge. More needs to be done to capitalize on the rich ideas about knowledge construction that some engineering students already have and to help other students become aware of the mechanisms through which they might develop deep engineering knowledge. This could take the form of direct discussions either early in their time as an engineering student or during second- and third-year courses. Professors can be more explicit in their courses about what it means to understand the material that they're teaching and aid students by suggesting ways to evaluate their own understanding. Looking more specifically at the problems in Study 2,

the most sense-making occurred when students were working on a concrete physical system (the tank problem), instead of the more abstract problems. Professors could help students approach these more abstract problems with an eye toward making sense of the mathematical operations instead of just using them to complete the problem. This mathematical sense-making would lead to constructing knowledge and aid them in their future careers as engineers. Engineering education can also build on the research of science educators and understand the effects of epistemology on framing on student problem solving (Gupta & Elby, 2011; Hammer, 1994; Lising & Elby, 2005). This research would illuminate more of the sources for difficulties with student problem solving and development of conceptual knowledge.

The findings of this dissertation also suggest that engineering students would benefit if engineering educators created more opportunities for students to discuss engineering science ideas with each other. The results of Study 3 show students already recognize discussion and explaining as ways to develop engineering knowledge. All the venues in which these students currently discuss engineering science ideas are informal, and opportunities for student-to-student talk are mostly self-created. Research on science education, and the episode of disagreement about exit velocity in Study 2, shows that there could be abundant opportunities for sense-making if educators encouraged student-to-student explanations and arguments. This practice could be implemented in a variety of ways. Previously established multiplied-choice conceptual questions (e.g. Koretsky et al.'s Concept Warehouse) could be used as prompts for class, organized recitation, or a new type of homework problem. New problems could be designed for recitation or homework that ask students to debate with each other about several possible

explanations, or write their own explanation that includes justification. Professors might also need to encourage discussion by being explicit about how knowledge is built through discourse and that the intended goal of certain activities is not to most efficiently get the right answer but to figure things out with other thinkers. Students conditioned to problem solving from prior engineering or science courses in college and high school might require explicit discussion to shift their epistemologies. Further research needs to be done on these types of problems, prompts, and activities, and on how problems that ask students to discuss and debate help support the development of conceptual knowledge. I encourage more studies examining student discourse during different types of engineering problems and tasks to understand how students develop engineering knowledge.

Finally, my findings indicate that it would be productive for engineering educators to consider the different types of problems they assign in engineering science courses and ask themselves what knowledge they want students to build. The evidence presented in this dissertation would support arguments for homework problems that ask student to 1) talk with one another 2) form explanations and arguments and 3) grapple with complex, real-world scenarios. As mentioned above, students already see discussing with and explaining to each other as a way to develop knowledge. Problems that ask students to do this in or out of class or through written assignments could help greater development of conceptual knowledge. Students in interviews also repeatedly mentioned the need for more real-world connections during lectures and contexts for assignments, and they voiced appreciation for professors who already do this in their teaching. The same students wanted more complex problems that require them to integrate different

types of knowledge and decide the most salient features of a scenario to incorporate into a model. Although these types of problems may be more difficult to develop and assess, undergraduates themselves believe they will help them become stronger problem solvers and more knowledgeable engineers.

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