The Complex Dynamics of Student Engagement in Novel Engineering Design Activities

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Abstract

In engineering design, making sense of “messy,” design situations is at the heart of the discipline (Schön, 1983); engineers in practice bring structure to design situations by organizing, negotiating, and coordinating multiple aspects (Bucciarelli, 1994; Stevens, Johri, & O’Connor, 2014). In classroom settings, however, students are more often given well-defined, content-focused engineering tasks (Jonassen, 2014). These tasks are based on the assumption that elementary students are unable to grapple with the complexity or open-endedness of engineering design (Crismond & Adams, 2012). The data I present in this dissertation suggest the opposite. I show that students are not only able to make sense of, or *frame* (Goffman, 1974), complex design situations, but that their framings dynamically involve their nascent abilities for engineering design.

The context of this work is *Novel Engineering*, a larger research project that explores using children’s literature as an access point for engineering design. Novel Engineering activities are inherently messy: there are characters with needs, settings with implicit constraints, and rich design situations.

In a series of three studies, I show how students’ framings of Novel Engineering design activities involve their reasoning and acting as beginning engineers. In the first study, I show two students whose caring for the story characters contributes to their stability in framing the task: they identify the needs of their fictional clients and iteratively design a solution to meet their clients’ needs. In the second, I show how students’ shifting and negotiating framings influence their engineering assumptions and evaluation criteria. In the third, I show how students' coordinating framings involve navigating a design process to meet clients' needs, classroom expectations, and technical requirements. Collectively, these studies contribute to literature by documenting students' productive beginnings in engineering design. The implications span research and practice, specifically targeting how we attend to and support students as they engage in engineering design.

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Chapter 1: Motivation and Intellectual Goals

This first chapter provides motivation and rationale for the dissertation. I open with an overview of current trends toward deficit-based views in engineering education research at elementary levels. I then turn to some less-cited research in engineering education that documents children's nascent abilities, and work from the Learning Sciences on *framing*, how students make sense of what they are doing as they participate in classroom activities. Lastly, I describe the intellectual goals of the present work: to understand the complexities and idiosyncrasies of student framing during open-ended design activities, and to show how their framings involve and are evidence of their engagement in engineering design.

Current trends in elementary engineering education research

To date, the majority of research on elementary engineering design has been shaped to align with curricular targets and education standards, taking the form of assessment instruments (e.g., surveys, knowledge tests) that measure students' knowledge of and about engineering and the design process[1]. These assessments are typically used as measures of program or intervention effectiveness (e.g., Dyehouse, Diefes-Dux, & Capobianco, 2011; Cunningham et

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[1] Beyond elementary levels, there has been much research on student learning at secondary and college levels, as well as research on teacher development in engineering subjects. Researchers have mainly sought to compare novice and expert behaviors (Atman, Cardella, Turns & Adams, 2005; Atman et al., 2007). Others have implemented assessment instruments to examine specific content areas, such as integration of science and math (Moore et al., 2014) and design process (Turns, Atman, & Adams, 2000), and modeling (Carberry & McKenna, 2011). At elementary levels, other areas include attitudinal studies (Cunningham & Lachapelle, 2010), teachers' self-efficacy in teaching engineering (Hynes, 2009), and assessment of initiatives and interventions.

al., 2005). In the following, I provide specific examples of assessment instruments and the corresponding findings. I then discuss why relying solely on these measures is problematic, and argue for expanding assessment to understand students' nascent abilities for engineering design.

Early studies in elementary education sought to probe students' conceptions of what engineers do. For example, Knight and Cunningham (2004), researchers from the Museum of Science in Boston, Massachusetts, developed the "Draw an Engineer Test," (DAET)[2] which prompted students to draw a picture of an engineer at work and to describe their pictures in writing. The researchers found that the majority of students (approximately 900 tested) associate engineering with fixing, building, and working on things, and portray engineers as physical laborers. Researchers from Purdue University repeated this study with different populations and found similar patterns (Oware, Capobianco, & Diefes-Dux, 2007). Their colleagues then extended the study by developing coding schemes to connect the patterns to STEM education standards and curriculum (Capobianco, Diefus-Dux, Mena, & Weller, 2011; Weber et al., 2011). In the latter, researchers identified four categories of "engineer" in students' drawings: engineer as mechanic who fixes engines, engineer as laborer who fixes, builds, or makes buildings, roads, and other structures, engineer as technician who fixes electronics and computers, and engineer as person who designs. The researchers concluded that new curricula should be designed to address students' existing conceptions and to help them learn key attributes of engineers (i.e., is creative,

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[2] Researchers based the "Draw an Engineer Test," on the previously used "Draw a Scientist Test" (Chambers, 1983).

uses science, uses math, uses technology, and works in teams) (Capobianco et al., 2011).

In related work, Cunningham et al. (2005) used the DAET findings to develop a second instrument that would probe students' conceptions about engineering and technology more systematically. Instead of providing a space for children to draw *one* image, the researchers developed an instrument with sixteen images of people doing work (e.g., cartoons of people improving machines, supervising construction, setting up factories, constructing buildings, making pizza). The researchers' objective was to make the instrument difficult, yet nuanced, "so only students with deep understandings would select all the correct items" (p. 2). Similar to previous findings, Cunningham and colleagues' (2005) results indicated that younger students tend to associate engineers with construction workers or train engineers, while older students think that engineers are car mechanics (repairing engines), laborers, technicians, or operators of large vehicles. Lachapelle et al. (2012) repeated the study and found similar results, concluding that students "have limited and often incorrect views of what engineers do and what technology is" (p. 12).

In related work, scholars in elementary engineering education focused on measuring students' knowledge of the engineering design process using both multiple-choice questions and interview-based protocols. For multiple-choice questions, researchers used the five-step *Engineering is Elementary*[3] (EiE) design

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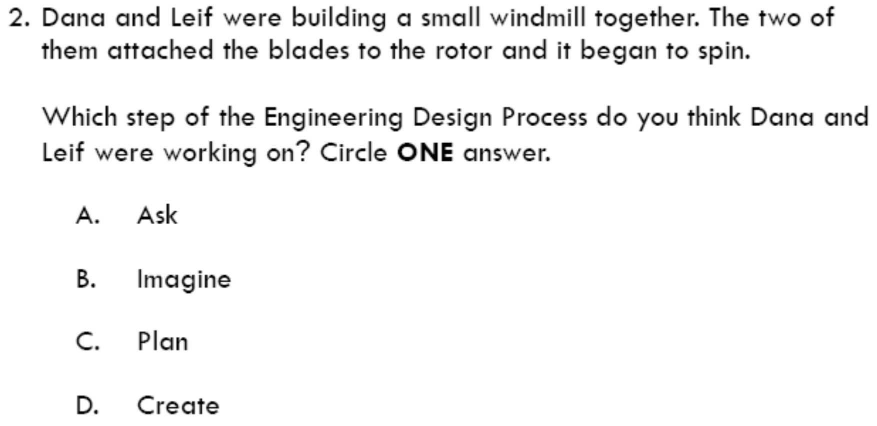
[3] *Engineering is Elementary* (EiE), a curriculum developed by the Museum of Science in Boston (www.mos.org/eie). The EiE curriculum is designed to teach elementary students about concepts in engineering and technology through a series of units organized by content.

process (Ask, Imagine, Plan, Create, Improve) as the canonically correct form (Cunningham & Lachapelle, 2007). For interview protocols, researchers used a slightly different eight-step process[4] and provided a context for design (Cardella, Hsu, & Ricco, 2014; Hsu, Cardella, & Purzer, 2012; Tafur, Douglas, & Deifes-Dux, 2014). Despite differences, the multiple-choice questions and interview protocols both measured students' abilities to identify design process steps and the sequence in which steps occur. Cunningham & Lachapelle (2007) provide the following example of a multiple choice question.



2. Dana and Leif were building a small windmill together. The two of them attached the blades to the rotor and it began to spin.

Which step of the Engineering Design Process do you think Dana and Leif were working on? Circle **ONE** answer.

A. Ask

B. Imagine

C. Plan

D. Create

Figure 1-1: Design process assessment question

After disseminating the test, Cunningham and Lachapelle (2007) found that students who had the EiE units were significantly more likely to choose the correct answers on the post assessment than on the pre assessment.

The interview-based protocols were developed to measure design process content knowledge is a slightly different way. In the interviews, researchers told students about a fictional student participating in an egg drop contest, and showed them an illustration of the fictional student's design process (Cardella et al.,

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[4] The eight-step process had been used in previous studies with college students (Bailey & Szabo, 2006).

2014). Researchers then asked the students what they thought was good about the fictional student's process, and what they would have done differently. The researchers coded the students' responses for design steps, or "concepts," and aligned them with the steps of the design process in EiE units. Their findings indicated that most students missed the "Ask" category, and that there were grade-level differentiating categories (e.g., Plan, Imagine, Test) that separated high and low scorers.

Lastly, researchers developed a composite instrument, or a "Student Knowledge Test," (SKT) to measure students' knowledge of engineers, engineering, the design process, and content objectives (Dyehouse, Diefes-Dux, & Capobianco, 2011; Tafur, Douglas, & Diefes-Dux, 2014). Researchers included previously developed questions on engineering and the engineering design process, and extended the test to include multiple choice questions on engineering vocabulary, such as design, engineer, properties, technology, and materials, and on specific content areas related to the EiE units. Researchers used the SKT to measure changes in student knowledge of EiE content before and after EiE interventions and across grade levels (Dyehouse, Diefes-Dux, & Capobianco, 2011; Tafur et al., 2014). For example, Tafur and colleagues (2014) used the instrument to measure change in elementary (Grades 2- 4) students' knowledge over two consecutive years of instruction (each year involved fourteen hours of teacher instruction). Tafur and colleagues (2014) found that students who had received instruction scored significantly higher scores on the post test, which they interpreted as improved understandings of engineering design content.

Why assessment-driven research trends are problematic

The methods outlined above (i.e., written surveys, assignments, or content-focused interviews) have been driven by practical aims, such as assessing teacher professional development program impact (Dyehouse et al., 2011), evaluating intervention effectiveness (Tafur et al., 2014), and identifying target areas for instruction (Capobianco et al., 2011; Cardella et al., 2014). These forms of measurement, which are widely used in engineering education (Koro-Ljungberg & Douglas, 2008), allow researchers to collect large data sets and to compare student knowledge across time and geographic locations (Duncan & Hmelo-Silver, 2009; Litzinger, Lattuca, Hadgraft, & Newstetter, 2011; Crismond & Adams, 2012).

In this section, I argue that the current trend in elementary engineering education research is problematic for two reasons: (1) the focus on students' declarative knowledge *of* and *about* engineering does not reflect the situated nature of disciplinary engineering design, which is inherently "messy" and "ill-structured" (Jonassen et al., 2006; Schön, 1983), and (2) researchers' methods, which typically involve content-based assessment instruments, do not provide insight to students' engineering abilities. These two aspects are tightly entwined: researchers' methodologies are based on and informed by their underlying theories of knowledge and learning (Crotty, 1998).

Knowledge of and about engineering. In developing the described assessment instruments, researchers make tacit assumptions regarding the knowledge that is valued in engineering education (i.e., declarative, definitionbased facts about engineering), and the ontology of engineering knowledge (i.e., contextually-independent information). The assessments typically involve vocabulary questions with clear distinctions between right and wrong answers, and students are expected to recall the definitions when taking the test. While these types of assessment questions facilitate large-scale collection and comparison of student knowledge of specific content, they do not access or capture the context-dependent, responsive, and reflective nature of knowing in engineering design (Schön, 1983).

To elaborate, the engineering design process assessments assume that steps of the process occur in a particular sequence and that those steps are mutually exclusive. In the example provided by Cunningham & Lachapelle (2007) (Figure 1-1), students were asked to circle which "ONE" step Dana and Leif are working on, and were given options of Ask, Imagine, Plan, and Create. The question implies that they are working on *only* one step and that the step occurs at a specific time. However, research on disciplinary engineering indicate that this is not the case; engineers in practice fluidly combine strategies of action throughout the process as they interact and negotiate with involved others, the design situation, and solution possibilities (Goel & Pirolli, 1992; Schön, 1983; Stevens, 2000). Instead of following design process steps *a priori*, engineers navigate their own processes as they evaluate designs in light of multiple dimensions, including material, social, economic, and stakeholder criteria (Bucciarelli, 1994/2002; Stevens & Hall, 1998; Suchman, 1987; Trevelyan, 2010).

Based on professional accounts, it is more likely that Dana and Leif would have enacted multiple design strategies as they attached the blades. They may have asked questions regarding functionality and mechanics, imagined and planned alternative connections, or evaluated their selection of materials. Their decision to “Create” a prototype would not likely be predicated on their completion of three prior steps, but instead would be an action they negotiated as being logical and informative.

These forms of assessment may also have indirect implications for teaching and learning engineering. Engineering practitioners have expressed concern that the emphasis on correct content, specifically the static, step-by-step design process, does not reflect the complexity of the discipline, nor does it prepare students for real world problems (Brophy, Klein, Portsmore, & Rogers, 2008; Bucciarelli, 1994; Johri & Olds, 2011). Further, being tested on engineering content may lead students to assume that there is *right* way to follow a design process, such as when to “ask” in relation to “plan” (Hennessy & McCormick, 1994; Johnsey, 1995). Schön (1983) describes why learning engineering as a discretized set of steps is problematic:

> Designing is a holistic skill (which) one must grasp as a whole in order to grasp it at all. Therefore, one cannot learn it in a molecular way, by learning first to carry out smaller units of activity and then to string those units together in a whole design process; for the pieces tend to interact with one another and to derive their meanings from the process in which they are embedded (p. 159).

In the following, I argue that the focus on declarative knowledge and reliance on assessment instruments limit research. More specifically, I argue that measuring students' knowledge of and about engineering design does not provide insight to their abilities to engage in disciplinary engineering design.

Limiting methodologies. In studies described above, researchers used assessment instruments to measure student knowledge and performed statistical analyses to interpret results. The researchers' methods and questions reflect their theoretical perspectives and implicit epistemological commitments – their tacit assumptions regarding the nature of knowledge and learning engineering (Crotty, 2003). For example, Tafur et al. (2014) ask, *How do students' knowledge change over two consecutive years of instruction?* Similarly, Cardella et al. (2014) ask, *Are there discernible differences in elementary students' of different grade levels' understanding of the engineering design process? If so, what are the differences?* The substance of researchers' questions and their corresponding methods for measurement implicitly assume that engineering knowledge is a static collection of information, that learning is the process of receiving and recalling facts, and that assessment involves measuring abilities to recall facts.

The instrument-based approaches to research are not unique to elementary-level engineering education; surveys and tests are prevalent forms of assessment in Engineering Education literature. Many of these instruments are devised to test hypotheses and to determine cause-and-effect relationships between variables (Creswell, 2007). Borrego et al. (2009) describe that this approach follows a specific recipe involving a theory or hypothesis, a purpose statement, and a direction of the narrowly defined research questions. These characteristics are explicit in Dyehouse et al.'s (2011) study: researchers examined students' domain-specific knowledge before an EiE unit, provided "treatment," or instruction, and then measured students' domain-specific knowledge to detect changes. Their methodology implicitly assumes students to be recipients of knowledge, and knowledge tests to be evidence of both student learning and intervention success. I argue that these approaches to research are problematic as indicators of student learning; while they provide concrete findings and testable cause-and-effect relationships (via student knowledge scores), they do not provide insight to the complexity of student learning in engineering.

In the following, I discuss less cited areas of Engineering Education literature that assume different perspectives and methodological approaches than the current trend. Rather than measuring students' abilities to retain specific knowledge, these researchers explore students' abilities to engage in engineering design. In aligning my work with these perspectives, I describe how I will contribute to the literature theoretically and methodologically.

Findings in theory-driven research

Although research on elementary students' engineering abilities is sparse in the mainstream engineering education literature, there is research in related journals (i.e., Science Education, Learning Sciences) as well as findings published from this work, that are pushing the field to consider students' abilities to engage in engineering. These accounts indicate that elementary students engaging in engineering design have abilities for reasoning and acting as beginning engineers:

they navigate their own design processes by interacting with the social and material elements of the design situation (Roth, 1995, 1996), reason about uncertainty (Jordan & McDaniels, 2014), and scope complex problems (Watkins, Spencer, & Hammer, 2014).

For example, Roth's (1995, 1996) study of fifth graders engaging in engineering illustrates how the students iteratively shape and reform their goals as they "construct, reconstruct, resolve, and abandon multiple interacting problems" (p. 366). Instead of following a sequence of design process steps, the students attend to different aspects of problems, analyzing structural stability, function, and uses of specific materials and aesthetics, and consider trade-offs in their pursuit of optimal solutions. Similarly, in their analysis of student discourse, Jordan et al. (2014) show how students collaboratively manage multiple aspects of uncertainty in engineering design by enacting strategies to cooperatively manage, negotiate, and clarify vague or ambiguous dimensions of the design situation.

Lastly, colleagues on the Novel Engineering research project developed qualitative accounts to explore students' problem scoping abilities (Watkins, et al., 2014). The researchers analyze three episodes of elementary students' problem scoping, detailing the complexity in students' design behaviors and describing how students' actions are in service of meeting clients' needs. In contrast to more typical methods of characterizing problem scoping, which often rely on simple codes and counts, their analyses capture ways in which students, like expert designers, explore multiple perspectives, refer to context when decision making, and prioritize different problems.

Drawing from the Learning Sciences to understand engineering learning

The need for change and methodological innovation have not gone unnoticed in engineering education; scholars in the community have raised concerns regarding the dearth of rigorous, qualitative approaches in Engineering Education (Borrego, Douglas, & Amelink, 2009; Case & Light, 2011; Koro-Ljungberg & Douglas, 2008; Olds, Moskal, & Miller, 2005). The centennial volume of *Journal of Engineering Education* (JEE) charges researchers to advance engineering education through interdisciplinary research and scholarship. In JEE's special issue, Johri and Olds (2011) assert that Engineering Education research, while growing, lacks theoretical and empirical rigor in engineering learning, and call researchers to draw from the field of Learning Sciences. They argue that Engineering Education researchers do not often consider the situated nature of learning and action, which they believe is imperative for developing theoretical insights in engineering learning. More specifically, they call researchers to account for social and material contexts, the roles of activities and interactions, and ideas around participation and identity in relation to learning engineering. Their argument has important methodological implications; they are urging researchers to extend beyond assessments that target transmission and acquisition of knowledge to include phenomenological aspects of learning that unfold in rich, multilayered learning situations, both in and out of classrooms (Brown, Collins & Duguid, 1989; Greeno & Engstrom, 2014).

In general, Learning Science researchers study learning in diverse contexts using a variety of methodologies ranging from ethnographic studies to lab-based investigations. In addition to theoretical development, scholars in this field apply their findings to the design of learning environments. While the contributions are wide ranging, there are several topics relevant to Engineering Education, and more specifically, to this work, including framing (Hammer et al., 2005; Scherr & Hammer, 2009), physical intuitions (diSessa, 1988, 1993; Smith, diSessa & Rochelle, 1993), design (Roth, 1995, 1996), reasoning with tools and inscriptions (Cobb, 2002; Sfard, 2000), metarepresentational competence (diSessa, Hammer, Sherrin, & Kolpowski, 1991), and disciplinary engagement (Engle & Conant, 2002). Learning Science researchers have also developed innovative methodological approaches, such as design-based research or design experiments (Brown, 1992; Collins, 1992) and approaches for collecting and analyzing video data (Derry et. al., 2010; Jordan & Henderson, 1995).

A central aim in Learning Sciences research and the work described in this dissertation is to understand student engagement in authentic disciplinary practices (Sawyer, 2014). Researchers have evidenced different dimensions of students' disciplinary pursuits, such as epistemic agency (Scardamalia & Bereiter, 1991, 2006), productive disciplinary engagement (Engle & Conant, 2002), and affective dynamics within disciplinary engagement (Jaber, 2014). Hammer and colleagues' work (2005) contribute important theoretical and instructional implications for productive disciplinary engagement. Hammer et al.'s (2005) theory and findings suggest that mind is comprised of fine-grained, contextually sensitive cognitive resources (e.g., conceptual, epistemological, social) and learning is a cognitive state involving the activation of resources in locally stable, coherent structures (i.e., frames). In a series of empirical studies, Hammer and colleagues show that students' disciplinary engagement reflects activation of productive frames. That is, students' understandings of what is taking place in particular moments may involve articulating ideas, interacting with the conceptual substance of each other's ideas (Hutchinson & Hammer, 2010; Scherr & Hammer, 2009) and using evidence to support their ideas to peers (Berland & Hammer, 2011). This view emphasizes productive aspects of students' existing knowledge – the everyday resources students have and bring to bear in learning contexts. As I discuss in Chapter 2, this work is foundational to my research, particularly in examining and characterizing aspects of student framing that are productive for engineering design.

Intellectual goals and contributions

In this dissertation, I contribute to Engineering Education literature both theoretically and methodologically. By providing empirically-grounded accounts of students' engineering engagement, I advance theory on elementary students' abilities to reason and act as engineers. From a methodological standpoint, I diversify the existing literature by conducting in-depth qualitative analyses. In a series of case studies, I show the complex and nuanced ways in which students engage in engineering in socially and materially-saturated classroom ecologies. While the series of studies are interwoven, each explores a unique strand: in the first, I turn to Stella and Alexi to explore framing stabilities; in the second, I compare two groups whose framings dynamically shift and evolve as they interact with materials and artifacts; in the third, I examine students' within-moment coordination of framings as they navigate their own engineering design process to develop an optimal solution.

This work calls the Engineering Education community to reconsider current ways of conceptualizing, attending to, and seeking evidence of student engagement in engineering design. I argue that current perspectives are limiting in the sense that they may blind researchers to the vast array of resources students bring to engineering design situations. My aim is to expose the context-dependent nature of knowledge through rigorous analyses on multiple levels of student reasoning and acting, rather than make generalizations about specific engineering knowledge. In doing so, I hope to illuminate the idiosyncratic – and sometimes unanticipated – ways students enact engineering abilities in open-ended design activities. In Chapter 7, I describe theoretical contributions and pedagogical implications, particularly the importance of recognizing and supporting the beginnings of engineering in elementary students.

Chapter 2: Theoretical Framework

My research objectives are grounded on the constructivist belief that children have nascent abilities, such as patterns of reasoning (e.g., analyzing, evaluating, negotiating) and acting (e.g., constructing, iterating, testing) that resemble disciplinary engineering practices. In the following, I describe how a resource-based view of knowledge provides a useful theoretical lens and language for (a) characterizing a wide range of students' intuitive ways of knowing in engineering, and (b) attending to the dynamics of student framing (Hammer, 2000; Hammer & Elby, 2002/2003; Hammer, Elby, Scherr & Redish, 2005; Redish, 2004; Tannen, 1993).

A resources-based view

A resources-based view of knowledge, reasoning, and epistemology describes that an individual's theories or beliefs are comprised of a collection of fragmented intuitions or "knowledge in pieces" that are learned and rearranged over a lifetime of experience (diSessa, 1993). From this perspective, students have a vast array of abilities – resources that they bring to the classroom – and they activate, arrange, and refine their resources when learning (Hammer et al., 2005; Smith, diSessa, & Roschelle, 1993/ 1994). Reasoning, in this view, involves activations of resources, such as conceptual resources for understanding causal mechanisms (diSessa, 1993) or mathematical expressions (Sherin, 2001), epistemological resources for understanding learning (Hammer & Elby, 2002), as well as social and affective resources for interpreting situations.

A resources view of knowledge provides a theoretical basis for framing (Conlin, Gupta, & Hammer, 2010): a frame exists as a locally coherent pattern of resource activations – "coherent" in that the pattern holds together for some length of time and "local" in that the coherence may be particular to the moment or context (Hammer et al., 2005). The central idea of framing is Bartlett's (1932) theory of "schemata," or knowledge structures that individuals build through experience and use in making sense of subsequent situations. Framing a situation involves tapping into cognitive structures of expectations and adapting those expectations based on the present situation. Researchers have explored framing phenomena in sociology (Goffman, 1974), sociolinguistics (Tannen, 1993), and cognitive science (Minsky, 1975), and, more recently, education (Berland & Hammer, 2009; Hammer, Elby, Scherr, & Redish, 2005; Hutchinson & Hammer, 2010; Scherr & Hammer, 2009). In the following, I describe the relevant literature, focusing on framing in classroom settings.

Theory to classroom

In classroom settings, a student's framing influences how she thinks about knowledge, navigates social situations, and engages in activities. Researchers have shown that students' framings interact with their learning on a moment-by-moment basis: a student may frame a physics problem as an occasion to use rote formulas in one moment and as an opportunity for sense-making in another (Hutchinson & Hammer, 2010). Scherr and Hammer (2009) show that students working in groups on a physics assignment may send and receive tacit signals, or "meta-messages" (Bateson, 1972) with information for interpreting the activity:

focusing eyes downward and whispering may signal framings for "completing the worksheet," while prolific gesturing and animated faces may signal framings for "discussing ideas" (p. 155). The researchers show that students' behaviors correspond to and interact with their local epistemologies: when framing as "completing the worksheet," students may interpret learning as getting the right answers, and when framing an activity as "discussion," they may engage in learning as an opportunity to make sense of phenomena.

Similar framing dynamics unfold in engineering activities: students draw from their previous experiences when framing design situations, and their framings interact with their ways of reasoning, acting, and engaging in engineering. For example, students' framings may involve considering clients or testing to see if their designs function; they may also involve using craft materials (cardboard, paper, glue) to come up with fantastical ideas and stories. From a resources perspective, examining students' framings provides insight to their nascent resources for engineering: framing the design activity as helping story characters may involve resources for empathy, perspective taking, identifying needs, while framing a design activity as building representations may involve their resources for thinking about scales and modeling.

Rationale

My rationale for a resources-based account of cognition is twofold: (1) it provides flexibility in attending to phenomena of interest, rather than examining for *a priori* constructs, and (2) it establishes ontological and epistemological continuity across cognitivist and situative/distributed traditions of learning

(Conlin et al., 2010). Many scholars have argued for research that bridges the cognitive and situative perspectives on learning (e.g., Greeno & van de Sande, 2007; Roth, 2001). These efforts are driven by the need to overcome the dichotomy between learning as acquisition (the cognitive perspective) and learning as participation (the situative perspective) (Cobb, 1994), and to see the two perspectives as being compatible and incommensurable (Sfard, 1998). With respect to data, this view translates to a dynamic unit of analysis; as Roth (2001) argued, to analyze cognition, researchers must focus on multiple "zoom" levels, extending beyond the mind to the individual's environment.

By taking a resources view of knowledge, I bridge dynamics at the level of student discourse and models of individual cognition (Brown & Hammer, 2008). From a situative perspective, I account for the contextually sensitive nature of framing to investigate how students' social and material interactions involve their sense-making within and about an engineering design activity. From a cognitivist perspective, I explore the emergence of students' engineering "habits of mind" (Dym et al., 2005) or disciplinary "ways of knowing" (Cross, 2006), the patterns in student reasoning that resemble those of practicing engineers.

Chapter 3: Design Context and Methodology

Research context

This research is part of an exploratory research project entitled Novel Engineering that is funded by the National Science Foundation (DRK-12 grant 1020243). Novel Engineering is an instructional approach that involves using children's literature as an access point for engineering design; story characters become students' clients and the story setting provides a rich design context. Since 2011, we have been working with approximately ten to fifteen elementary teachers (Grades 3 – 5) per school year in nine schools of varying demographics. Our work with teachers has involved facilitating professional development experiences during the summer and the school year, co-developing classroom lessons and activities, and supporting teachers in classrooms during implementation.

Project philosophy and approach. The Novel Engineering approach is unique in that it does not involve a prescriptive curriculum. Instead, it is responsive to teachers' needs in the classroom, including their choices for books, time commitments, literacy goals, and assessment needs. In collaboration with elementary teachers, our research team is exploring the affordances of Novel Engineering activities with a variety of book genres, lesson structures, and building materials. Much of our interest is in understanding what may come of these choices, particularly with respect to the students' learning of engineering design and their development of literacy skills. Our findings indicate synergistic advantages to integrating engineering and literacy. Stories provide multidimensional problem contexts, fictional clients with needs, and implicit constraints that may enable students to engage in engineering reasoning and actions; in turn, developing optimal solutions for their clients motivates students to draw inferences from and attend to details in the text.

Project research. Our current research efforts involve exploring the potential advantages, as well as the challenges and implications, in greater depth in the areas of student learning and teacher development. Our research team aims to contribute to and advance educational research by conducting empirical analyses of student learning in areas of engineering and literacy. From an engineering perspective, we are characterizing students' abilities for engineering design, such as their ways of framing problems, planning and developing solutions, and realizing and testing their ideas. We are examining the emergence of those abilities across a range of book genres and lesson structures (e.g., McCormick, 2014; McCormick & Hammer, 2014; McCormick & Hynes, 2012; McCormick & Watkins, 2015; Watkins et al., 2014). From a literacy perspective, we are examining the ways in which an engineering task supports and provides insight into students' reading comprehension, perspective-taking, and interaction with the text. By documenting recurrent themes across classrooms and activities, we aim to develop evidence-based explanatory frameworks around students' emergent abilities to reason and act as engineers. Our overarching goal is to develop informed instructional approaches and practices to cultivate and to support elementary students' abilities for engineering design.

Our central objective in research on teacher development is to understand how teachers attend and respond to student thinking during Novel Engineering activities. In this, we identify aspects of teachers' ideas about and conceptions of engineering learning, self-efficacy in teaching engineering, and pedagogical content knowledge, or knowing about teaching engineering (McCormick, Wendell, & O'Connell, 2014; Wendell, 2014). By conducting longitudinal studies with participating teachers, we aim to develop informed professional develop approaches to support teachers in creating and implementing learning experiences to foster student development of engineering reasoning and practices, such as problem framing, conceptual planning, realizing and testing design ideas, and attending and responding to student thinking in ways that sustain student agency and engagement in engineering design.

Methods

In this section, I describe the context and design features of the study and the research methodology, including the scope of data, selection of classroom episodes, and analytical methods I used to construct and support claims about data. By drawing from multiple sources and tools, I take a pragmatic approach in an effort to examine phenomena of interest. In Gee's (1999) words, I assume methods to exist "not (as) a set of rules, but rather (as) a set of thinking devices within which one can investigate certain sorts of questions, with due regard for how others have investigated such questions, but with adaptation, innovation, and creativity as well" (p. 9).

Overview. Our research team's approach reflects a design-based research methodology in that we are (a) iteratively conducting research in classroom and professional development settings (Brown 1992), (b) flexibly revising procedures and approaches throughout the project (Design-Based Research Collective, 2003; Collins, 1999), and (c) aim to develop empirically grounded theories through combined study of both the process of learning and the means that support the process (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; diSessa & Cobb, 2004; Gravemeijer, 1994, 1999 Kelly, 2004; Shavelson, Phillips, Towne, & Feuer, 2003). In the following, I describe how our team collects data in classrooms and how we select, bound, and analyze data.

Data collection. Our research team has been collecting data for the Novel Engineering project for four years. Our data consist of audio and video recordings during classroom implementation, professional development, and interviews, and also paper-based and photographic data of students' work, and reflections. As previous researchers have noted, videos provide a medium for analyzing naturally occurring phenomena, allowing researchers to see the flow of activity, while also revisiting and reanalyzing moments in greater depth (Derry et al., 2010; Hall, 2000).

During classroom activities, members of our research team set up small, tripod-based cameras on randomly selected student groups, often with additional microphone units to capture sound adequately. In addition, we take field notes while in classrooms and interact with students as they participate in the activity. Over the course of the project, we have collected hundreds of hours of video footage from participating teachers' classrooms, professional development workshops, and after-school meetings with teachers. These videos, photo and electronic copies of students work, and researchers' field notes are the primary sources of data in this project.

Data selection. Detecting and investigating the dynamics of student engagement involves attention to multiple dimensions of ongoing activity, which vary in scale and nature (e.g., student talk, classroom norms). To unpack these dynamics, our team selects and transcribes video data from classroom activities to view in research meetings. Collaborative viewing of data plays a central role in our research process, often involving iterative analysis and/or refinement of interpretations of student learning in light of new findings and theoretical perspectives. When viewing video data, our research team attends to student discourse (Gee, 1999), including their vocal and spatial modalities, such as pauses, interruptions, as well as gestures, shifts in participation patterns and in the orchestration of talk and turn-taking (e.g., Goodwin, 2000, 2007), and interactions with objects and materials in the classroom (Jordan & Henderson, 1995; McDermott, Gospodinoff, & Aron, 1978).

We select and transcribe classroom episodes that require in-depth analysis. Many of the videos we clip for in-depth analyses involve students constructing, evaluating, testing, or reasoning about elements of their projects. For the first two studies presented in this work, I have bound data to form episodes that evidence the complex dynamics of student framing, such as how students are orienting to the task objectives or defining constraints. In the third study, I analyzed all available data for one group, and conducted in-depth analyses for selected episodes. I further describe data selection and bounding in each of the three component studies.

Analytical approach. I draw from a range of analytical tools with the aim of interpreting the phenomenology of student framing during Novel Engineering activities. In doing so, I aim to capture the lived experience of students in terms of their own meaning making activities – how they form a sense of the activity, and how their sense influences their reasoning and acting. Methodologically, examining and describing emergent patterns and transitions in students' framing necessitates coordination of multiple levels of analysis with varying foci that range in time scale and grain size. By assuming a dynamic unit of analysis, I employ an analytic method of "zooming" to examine phenomena of interest (Roth, 2001), specifically related to student sense-making about the task (Conlin et al., 2010; Mandelblit & Zachar, 1998).

In analyzing video data, I draw on methods from interactional analysis (Jordan & Henderson, 1995), discourse analysis (Gee, 1999), and conversational analysis (Goodwin & Heritage, 1990; Schegloff, 2007. I focus mainly on students' verbal and nonverbal interactions and their interactions with their local environment, including materials, classroom norms and rituals, and the setting of the design. I use discourse analysis tools, the linguistic cues and markers that form a "structural basis for analyzing talk" (Gee, 1999, p. 34), to examine the relation between cognitive processes and the settings within which those processes takes place. This analytical approach builds on my theoretical framework[5], allowing for simultaneous analysis of two layers (cognitive and situative) that are reflexive and mutually constitutive. That is, the substance of an individual's reasoning involves, informs, and is evidence of the student's framing of what is going on in that situational moment (Goffman, 1974; Hammer et al., 2005; Hutchinson & Hammer, 2010), which is reflected in how the individual interacts with others and the environment (see Scherr & Hammer, 2009).

Investigating student learning and engagement in engineering design contexts necessitates attention to what students understand the task to be about – their framings of the activity – and the kinds of epistemic activities that are a part of those framings. Each of the main three component studies (Chapters 4, 5, and 6) has unique analytic foci and structuring of data and analysis. The first two (Chapters 4 and 5) take the form of case studies to gain in-depth investigations into the stability in student framing and in the dynamic transitions and fluctuations that occur as students interact with materials and artifacts in the classroom. A case study approach is particularly appropriate for addressing my research questions, which require in-depth analyses of students' talk and interactions occurring within rich and multidimensional classroom contexts (Case & Light, 2014; Lincoln & Guba, 2000). The third study (Chapter 6) builds on the first two case studies. In this study, I draw from previous work to develop and illustrate a coding scheme to capture the emergent patterns in framing dynamics.

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[5] As noted in the theoretical framework, a resources perspective establishes theoretical continuity between cognivitist and situative perspectives. This also aligns with the notion of "situated cognition" (Roth, 2001) in examining phenomena at the level of cognitive units, or epistemic agents (Cobb, 1994; Cobb, Wood, & Yackel, 1993), in conjunction with the local situational surroundings (e.g., social interactions, materials, cultural norms) that give rise to forms of reasoning in situations.

My purpose in doing so is to examine the dynamics of student framing *within* moments to understand how individual group members coordinate and co-construct framings as they navigate an engineering design process. Because my research questions address different aspects of the data, they require slightly different analytical tools for investigating different levels, grain sizes, and foci. Each of the three studies contains it's own Methods section with a description of specific contexts and analytical tools.

Chapter 4: Stable Beginnings in Engineering Design

Novel Engineering activities are premised on the integration of engineering and literacy: students identify and engineer solutions to problems that arise for fictional characters in stories they read for class. There are advantages to this integration, for both engineering and literacy goals of instruction: the stories provide “clients” to support students’ engagement in engineering, and understanding clients’ needs involves careful interpretation of text. Outcomes are encouraging, but mixed, in part for variation in how students frame the task. For instance, while students often pay close attention to the stories, interpreting and anticipating their fictional clients’ needs, they sometimes focus more on the teacher and what they think she would like to see. This variation occurs both within and across groups of students, and it motivates studying the dynamics of student framing. Here, we examine a pair of students who share a central objective of designing an optimal solution for their fictional client, and who persist in achieving their objective. We argue that the students’ stable framing of the activity involves their engagement in engineering design, and that the abilities they demonstrate in pursuit of a solution are evidence of their productive beginnings in engineering design.

Stable Beginnings in Engineering Design

Introduction

The following excerpt takes place in a fourth grade classroom in a rural New England town. Two students, Stella and Alexi, are participating in a Novel Engineering design activity, an instructional approach in which students design and construct engineering solutions to problems that arise in literature. In the class, the students had read the novel *Shiloh* (Naylor, 1991) and were assigned the task of engineering a protective dog pen.

In setting up the task, Ms. C., the teacher, explained to students that they could use craft materials (e.g., cardboard, tape, glue, felt, etc.) to create a dog pen that would "fit on their desk" and will protect Shiloh, a small beagle in the story, from danger. Ms. C. noted that their designs will be "tested," but did not explicitly define the test. For the students, the nature of the task was inherently open-ended and loosely-defined: they had to design solutions to help fictional clients using classroom materials, and their designs would be tested in some way.

In the following exchange, occurring on the first day of the design activity, Stella and Alexi are working on their sketch (Figure 4-1) when Ms. C. asks them about their design decisions.

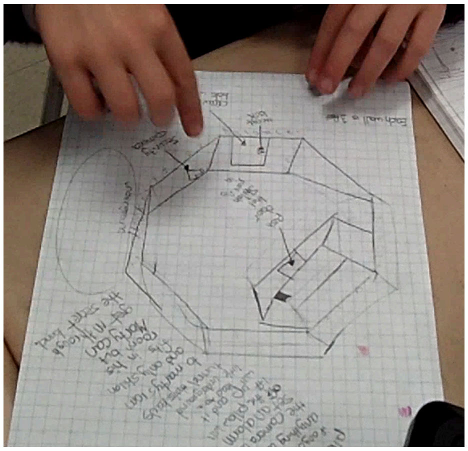

Figure 4-1: Stella and Alexi's design sketch

Ms. C.: What kind of entrance is it?

Stella: It's…

Alexi: Just a little door, like the walls are two feet.

Ms. C.: Two feet thick? Or two feet high?

Alexi: No, two feet high.

Ms. C.: Two feet high, okay.

Alexi: I wrote it on this side somewhere (flipping paper), here it is. Oh yeah, oh, it's three feet.

Ms. C.: Three feet! Wow. Why three feet? What made you decide three feet?

Alexi: Um, so it wouldn't be too short, like when Marty wants to go in, since it has, like, that glass that doesn't break on the top, he doesn't have to scrunch down (positioning her body to make scrunching gesture).

Ms. C.: Ah, so Marty could go in as well?

Alexi: Yeah.

Ms. C.: All right, very cool. Did the graph paper help you guys draw your diagram?

Alexi: Yeah.

Stella: Like, she did eight squares that way, and then six squares that way.

Ms. C.: Oh, so you're using measurement as well, excellent work!

As Ms. C walks away, Stella and Alexi continue by discussing the advantages and disadvantages of specific entrance locations, erasing, adjusting, and negotiating elements on their design sketch.

Our first purpose in this chapter is to argue that Stella's and Alexi's planning and reasoning evidence nascent abilities for engineering design. For example, Stella and Alexi consider their clients and what might help them, and they use graph paper to generate an appropriate scale. As they negotiate criteria (e.g. access, height, location) and constraints (e.g., abutting glass elements), they "prioritize the needs of their clients" (Ropohl, 1997, p. 70) ensuring that the boy in the story, Marty, will be able to access his beagle, Shiloh, and that he will do so easily and comfortably (Hughes, 1998). They generate multiple representations to analyze and evaluate features of their design, and come up with an appropriate scale to correlate their sketch and model to real-life dimensions.

As we show in this chapter, this interaction was not unique for Stella and Alexi; the data indicate that they maintained attention to their fictional clients and evaluated their design accordingly, even when confronted with competing sets of expectations for how they would be evaluated. Stella's and Alexi's stability in attending to and designing for the fictional clients was not a pervasive occurrence in the class; some of their classmates described design considerations as a way to show their knowledge of vocabulary terms (e.g. "stabilized" and "reinforced"), while others became more interested in repurposing craft materials in imaginary ways, sometimes as pretend technologies (e.g., "laser beams" and "mini bodyguards") rather than functional solutions or prototypes.

Our second purpose is to consider how Stella's and Alexi's pursuit of a design solution reflects their understanding of what it is they are doing. It is one thing to have abilities, for example, to scale a diagram; it is another thing to recognize a need to make use of those abilities. For the girls, scaling their diagram to "real life" was not part of their assignment; they realize the need to invoke mathematics as a measurement tool and use the back of their sketch to come up with an appropriate scaling factor for a life-size design. That is, part of the dynamics of their activity in this moment involves their understandings of "what is it that's going on" (Goffman, 1974, p. 8), for their client in the story as well as for them in the classroom, in other words their *framing* (Goffman, 1974; Tannen, 1993).

The productive aspects of the students' engagement, such as their ways of reasoning about design decisions and attending to client needs, are not common areas of focus in Engineering Education literature. Many researchers instead highlight ways that students act as novices relative to expert engineers (Crismond, 1997, 2001). For instance, scholars in the field have argued that students with little formal design experience, i.e., "beginning designers" (Crismond & Adams, 2012), may not fully grasp how complicated, fluid, and changeable design problem-solving landscapes can be (Dorst, 2004), or may be "unaware or unwary of the potential for cascading complexity" (Crismond & Adams, 2012, p. 747). Here, we take a different perspective on beginning engineers. Rather than assuming students with little or no formal training in designing are lacking in abilities, we show data that evidences students' nascent abilities – their productive beginnings in engineering.

In the following sections, we review current literature in engineering education, highlighting the need for research on student engagement in engineering design activities. We then discuss the construct of framing, in particular of epistemic activity (Hammer, Elby, Scherr & Redish, 2005; Redish, 2004), as a lens to interpret students' tacit understandings of an activity in a classroom setting and as applied to research on engineering (Dym, Agogino, Eris, Frey, & Leifer, 2005; Schön, 1983; Vincenti, 1990). Returning to Stella and Alexi, we examine their framing of the activity in three excerpts. In our analysis, we find that a central aspect of the girls' framing is their stability: they show resilience in understanding the activity as involving designing and presenting their ideas for the fictional clients. We then present a brief excerpt from another group of students who were comparatively less stable. In our discussion, we propose that part of Stella's and Alexi's stability was their involvement in the story itself, including their empathy for the characters. We close the paper with a discussion of further questions for research and possible implications for instruction.

Engineering in Classroom Settings

Much of the literature in engineering education makes explicit claims or tacitly assumes elementary students with little or no formal design experiences are lacking in engineering design abilities. For example, researchers who draw comparisons between inexperienced, or "novice," designers and experts find that novices may immediately try to solve the problem with little talk or forethought (Christian & Dorst, 1992). Others argue that novices may make premature commitments to initial solutions (Cross, 2000), or may treat design problems as well-defined textbook problems with clearly articulated initial states, identifiable collections of known variables, and set procedures for generating solutions

(Atman & Bursic, 1996; Rowland, 1992).

In other instances, researchers' assumptions regarding students' lack of engineering abilities are implicit, used as a basis for the development of instructional strategies in engineering design. In a seminal study, Crismond and Adams (2012) developed an "Informed Design Teaching and Learning Matrix" by providing detailed descriptions of contrasting behavioral patterns between "beginning" and "informed" designers, describing the former as having little or no formal design experiences and the latter as having formal design experiences. The purpose of the tool was to enable teachers to develop their own teaching strategies by recognizing the "highly ineffective practices and habits of mind that beginners employ," so that they could choose among appropriate teaching strategies (p. 741). Among the assumed "ineffective practices," Crismond and Adams (2012) characterize beginning designers as being more likely to attempt to solve a problem with little talk or forethought; skip research and move on to generating solutions immediately; start their design with few or only one idea; and enact design as a sequence of steps in their search for a solution. While Crismond and Adams (2012) recognize a critical need for educational research in areas of instructional approaches, they overlook the need for research on beginners' engineering design abilities that are productive. Further, they do not acknowledge that students may come into the classroom with nascent abilities.

Researchers from science education and learning sciences provide evidence that students do have abilities for engineering design: they navigate their own design processes by interacting with the social and material elements of the design situation (Roth, 1995, 1996), reason about uncertainty (Jordan & McDaniels, 2014), and scope complex problems (Watkins, Spencer, & Hammer, 2014). For example, Roth's (1995) study of fifth graders participating in a thirteen week engineering design module illustrates how the students iteratively shaped and reformed their goals as they "construct, reconstruct, resolve, and abandon multiple interacting problems" (p. 366). Rather than being "stifled by open-endedness" or "unaware of the potential for cascading complexity" (Crismond & Adams, 2012, p. 747) as beginners are assumed to be, the students attended to different aspects of problems, analyzing structural stability, function, and uses of specific materials.

In this article, we contribute to research that show students' productive abilities for engineering design. We argue that students' sense of what they are doing in a given activity – their framing (Goffman, 1974) – matters for the abilities that they enact. This argument offers explanatory insight to discrepant claim in the literature regarding students' abilities: if students frame the design activity as a traditional school activity, they are likely to treat it as such, a problem that is well-defined with clearly articulated initial states, identifiable collections of known variables, and set procedures for generating solutions (Atman & Bursic, 1996; Jonassen, 1997; Rowland, 1992). To solve these problems, they may enact strategies that they use for typical school activities, such as generating solutions immediately or enacting a sequence of steps in search for a solution, i.e., novice behaviors (Crismond & Adams, 2012). On the other hand, if students frame the design activity as an opportunity to construct and evaluate their own designs, they may demonstrate “uncanny competence” (Roth, 1995, p. 372) in dealing with complex design situations. In our data, we see evidence of the latter: Stella and Alexi navigate their own design process in pursuit of an optimal solution for their clients. Our goals are to understand how they are framing the activity, and how their framing involves their nascent abilities for engineering design.

Framing

In a given situation, whether it involves playing soccer, learning science, or designing a bridge, people form a sense of what is taking place, what researchers have called a “frame” (Goffman, 1974; Tannen, 1993). Forming that sense, or “framing,” reflects structures of expectations formed from previous experiences (Tannen, 1993). In these accounts, frames are knowledge structures that both shape and are shaped by experience, and framing is a dynamic interaction between expectations and perceptions. Frames are not static, rigid structures, but are active and responsive, perpetually evolving as they are informed, shaped, and tuned with new experiences; in this sense, they are “schemas” (Bartlett, 1932) of activity. “One’s structures of expectation make interpretation possible, but in the process, they also reflect back on the perception of the world to justify that interpretation” (Tannen, 1993, p. 20-21).

For Stella and Alexi, part of the challenge was to form a sense of their task, engineering for Marty and Shiloh, and that would involve their tapping into patterns of their previous experiences of telling stories, doing projects in school, making things, and so on. Part of the challenge, too, was in understanding the situation in the story. Their experiences similarly shaped their comprehension of the novel, in structures of expectations about caring for dogs, ownership and protection, and so on. At the same time, their experiences in this task contribute to those patterns, perhaps helping them understand future experiences. Reading the story, for example, may be their first encounter with the idea of an abusive owner; designing the protective pen may be one of their first experiences of engineering.

Epistemological Framing in Classroom Settings

There are many aspects to framing, at multiple scales and with complex, nested relationships. An individual who is baking has an overall sense of what baking involves, but may cue finer-grained framings within subtasks of measuring, mixing, frosting, etc. In Stella's and Alexi's case, their framing of being students in a classroom may be constituted by expectations for sitting at their desks, listening to their teacher or an adult in charge, and enacting certain actions for specific time blocks. Within that, they may activate frames for "learning science" that involve experimenting and making sense of phenomena, and other frames for "learning spelling" that involve memorizing sequences of letters. Thus, across and within different activities or classroom contexts, students activate and tune their expectations, including with respect to knowledge and learning, that is their "epistemological framing," (Redish, 2004).

Research in science education has paid significant attention to students' expectations with respect to knowledge. A variety of studies have documented students experiencing science class as focusing on the authority of the teacher or textbook (Hammer, 1994; Jimenez-Aleixandre, Rodriguez & Duschl, 2000;

Lemke, 1990; Redish, Steinberg & Saul, 1998), rather than on making tangible sense of natural phenomena. In these cases, students frame what they are doing as memorizing, storing, and reproducing known information, rather than, for example, producing and assessing knowledge. Recent accounts have built on this work by attending to the local dynamics of students' framing (Hammer, 2004; Louca, Elby, Hammer, & Kagey, 2004; Rosenberg, Hammer & Phelan, 2006), evidencing the sensitivity to features of context and social interactions. Researchers' findings indicate that for students to be actively learning science, they must not only frame what they are doing as sense-making about natural phenomena, they must do so with stability, e.g., for resilience against the familiar "classroom game" (Lemke, 1990) that focuses less on the natural world than on the authority of the teacher or text (Hutchinson & Hammer, 2010).

In this work we study how students frame their work in engineering. We are interested to understand aspects of framing that are productive for engineering as well as in the local dynamics, stabilities, and variations. As in science, students may frame what they are doing in ways that are counterproductive for engineering, including following a sequence of steps (e.g., Massachusetts Curriculum Frameworks, 2010), or assuming there is a single "right answer" (Hennessy & McCormick, 1994; Johnsey, 1995, 1997; Welch, 1995). Accordingly, research in engineering education often focuses on students' abilities to follow these steps, such as planning in the beginning of a design endeavor. In such cases, when students do not follow the prescribed sequence (e.g., planning while constructing), they may be diagnosed as lacking in engineering ability. A framing perspective, however, offers an alternative possibility: Students' understanding of what is taking place have them invoke abilities they have, e.g., for planning (Portsmore, 2010). This motivates attention in engineering education beyond abilities, both in interpreting students' work and in planning objectives for lessons, in particular to cultivate productive framings for engineering.

Productive Framing in Engineering

A view of framing sees engineers' understandings of design as involving patterns of familiar experiences, tuned to the particulars of situations. This is the heart of schema theory; a schema is "an active organization" of past experiences (Bartlett, p. 201), active to include local tuning. As Schön (1983) describes, engineers "are not confronted with problems that are independent to each other, but with dynamic situations that consist of complex systems of changing problems" (p. 16). In "making sense of a situation" (Schön, 1983, p. 40), an engineer maintains a heightened awareness of the overarching design task, while attending to the multiplicity of interacting subtasks (Dym et al., 2005). Accordingly, design tasks generally involve subtasks, and this is part of engineers' framings.

For example, an engineer's framing of a bridge design project may involve optimally meeting the client's needs while adhering to situational constraints. Within this overarching framing, the engineer is simultaneously recognizing subtasks, such as researching the environment, developing and analyzing computer models, and negotiating with contractors and community members. At each decision juncture, the engineer must reflect on the big picture, recognizing clients' needs and design constraints, and respond with appropriate modes of reasoning and action, such as analyzing, evaluating, constructing, etc. (Trevelyan, 2010).

Analogously, students' framing of a Novel Engineering activity may involve reflecting on the story and responding to characters' needs. Our early findings suggest that a story setting provides a sufficiently "messy" (Schön, 1983, p. 33) design context, in which story characters become clients with wants, needs, and potential dilemmas, and there are implicit physical, social, and economic constraints (McCormick & Hynes, 2012). Thus, in framing a complex design task as beginning engineers, students may recognize a need to reason, make decisions, and act as engineers: to develop an optimal solution for their client. We argue that engineering abilities, or "technical know how" (Ropohl, 1997), should not be our sole end goal in engineering education. Fostering productive framing should be a central target for research and practice, such that students recognize a need to use their engineering abilities.

Methods

Research setting. This study is part of an NSF funded project at Tufts University focused on integrated engineering and literacy. The primary goal of Novel Engineering is to support elementary school teachers in using children's literature as a context for engineering design activities. Participating teachers develop and implement Novel Engineering units using stories that are already part of their curricula. In preparation, teachers attend approximately forty hours of professional development per school year at Tufts University to work with researchers in developing lessons and implementation strategies. This case study takes place in a fourth grade classroom in a rural town in Massachusetts, about forty miles from Boston. The teacher, Ms. C, had attended approximately thirty-five hours of professional development as part of the Novel Engineering project and was excited to try a Novel Engineering activity using the book *Shiloh* (Naylor, 1991).

Data collection and analytic tools. Our research team's approach to collecting rich *in situ* data by videotaping reflects our interest in capturing the dynamics of students' understandings of what is taking place. As previous researchers have noted, videos provide a medium for analyzing naturally occurring phenomena (Derry et al., 2010). Further, video data provides researchers with temporal management in that they are able to see the flow of activity, while also revisiting and reanalyzing moments in greater depth. In this endeavor, video data is a powerful medium for attending to moments of student discourse, interactions, as well as paralinguistic channels of communication, including vocal and spatial modalities, such as pauses, interruptions, and gestures (Jordan and Henderson, 1995; McDermott, Gospodinoff, & Aron, 1978), which are often forms of meta-communicative messages or signals of one's framing (Bateson, 1972).

During classroom activities, researchers set up small, tripod-based cameras on randomly selected student groups, often with additional microphone units to capture sound adequately. In this study, two researchers, including first author, were present, providing materials, supporting teachers and students during building, as well as taking field notes and video recording.

In our analysis of video data, we draw on tools from discourse (Gee, 1998) and interactional analysis (Jordan and Henderson, 1995) with attention to both verbal and non-verbal aspects of the data to interpret students' framing of the Novel Engineering task throughout their design process (Hammer, 2004; Hutchinson & Hammer, 2010; Scherr & Hammer, 2009; Tannen, 1993). Collaborative analysis of student video plays a central role in our research process, often involving iterative reevaluation and/or a refinement of interpretations in light of new findings and insight from alternative theoretical perspectives (Derry et al., 2010). In our collaborative viewing of the data, our focus remained centered on students' framings of the activity, particularly with respect to how students' framings were informing and interacting with the substance of their reasoning and design decisions.

Analysis

For this activity, Ms. C. gave the students two hours per day for three consecutive days[6]: Day One involved class read-aloud, discussing the major problems in the book, and starting individual plans; Day Two involved working with a partner on design plans and building, and Day Three involved finishing designs followed by group tests and presentations.

In the following, we show three excerpts of Stella's and Alexi's work. Although these excerpts are presented in chronological order, our selection of data

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[6] This includes the hands-on component of the activity. The entire activity extended over 3 weeks, which included daily read-aloud and discussions for varying lengths of time.

is not based on the phase of activity or day. We highlight these moments to show evidence of how they frame the task, and the stability with which they do so. In the first excerpt, Stella and Alexi explain their design decisions, focusing on their fictional clients' needs. In the second and third, they show resilience in this framing against competing expectations regarding testing and evaluating criteria. We then show brief snippets of data from other groups in the same classroom who were comparatively less stable in their framing.

Design considerations (Day One)

During the initial phase of their design, all of the students in class are working in pairs or groups of three to co-construct a sketch of a dog pen for Shiloh. When the materials for building (e.g., cardboard, paper, glue, etc.) become available, many students rush to grab them. Others, including Stella and Alexi, continue to work on the details of their design sketches. In the following, the first author asks the girls about their work.

Mary: That's a cool design. What is, so what do you have?

Alexi: It's like, in this [unclear], and there's a little lock, so Marty can just turn the lock, and there's a little door that Shiloh just fits in. And if the camera sees something that it doesn't recognize, like, if it's not Marty's family or something, or if it's something else, it'll, like, this door will go automatically open, and the pillow will come out, and there's underground tunnels, and there's, like, a little, um, there's kinda, like, a little box in here — I kinda drew dotted lines.

Mary: That's really cool!

Alexi: -and then there's tunnels leading to Marty's room, and an alarm will go off in Marty's room, so he can just crawl through the tunnels and get to Shiloh.

Mary: Oh, that's really cool! So you're thinking about how Marty can — is Marty the owner of the dog?

Alexi: Yeah.

Stella: Well, not necessarily the owner…

Alexi: But he wants to be the owner!

Mary: (laughing) He wants to be!

Alexi: So that's why he's trying to keep it very secret.

The girls focus on keeping Shiloh safe, comfortable, and accessible to Marty. They describe the functional issues of the tunnel connection, with attention to details from the story: the tunnel is accessed only through the pillow door, and provides a direct route for Shiloh to Marty's room. As they imagine Shiloh's escape route, they consider multiple perspectives: Alexi describes the path Shiloh will take to get to Marty's room, as well as a way for Marty to be alerted so he can quickly rescue Shiloh in the case of danger. They develop contingency plans to account for implicit "what if" circumstances, such as sizing the tunnel door so that "just Shiloh fits in," in case the bigger dog gets past the first barrier, while maintaining fidelity to "must haves" (i.e., a door to the pen) (Schön, 1983, p. 101). Although keeping Shiloh hidden or "secret" was never discussed as a classroom requirement, Stella and Alexi prioritize this criterion, realizing that if he is caught, he will likely be abused again.

Stella and Alexi coordinate their overarching design goals of keeping Shiloh safe and secret with subtasks of developing and evaluating components. Their decisions are not driven by the classroom requirements of size and testability, but by the girls' interpretation of the physical and social setting of the story. These considerations, we argue, are evidence that they are framing the engineering design task as an opportunity to solve a problem for their fictional clients.

How Do You Test It? (Day Two)

At the start of Day Two, with the class assembled as a whole, Ms. C. calls on Stella to summarize the requirements.

Ms. C.: Stella, can you give a quick summary of what our requirements would be?

Stella: Oh, okay. Um, must fit on top of our desk and the test must be able to fit inside (referring to "inside" the dog pen).

Ms. C.: Whatever we choose, however we choose to test, it (referring to testing object) must be able to fit inside (the dog pens) so we can see if Shiloh would be able to get out and if something would be able to get in. And there was one more on the bottom, it has to be some sort of...

Stella: Pen.

Ms. C.:Pen, right? Some sort of enclosure.

The students' design task, as Stella remembers, is to construct a model of Shiloh's dog pen that is scaled to "fit on top of our desk," and the scaled model must be functional. Ms. C. confirms and elaborates several criteria for the test, referring to a wind-up toy they will use in class to represent Shiloh: (1) the object must fit inside the model; (2) the model must have boundaries that will prevent the object from leaving ("we can see if Shiloh would be able to get out"); and (3) the model must be protective in that it keeps outside objects from getting in.

As the students in the class construct their pens, they all evaluate their projects as they are working in pairs, but by a wide range of criteria. For instance, while some evaluate based on how well it will work for Marty and Shiloh, others prioritize "classroom" expectations, anticipating how their projects will be assessed in comparison to their classmates'. In the following, Stella and Alexi are working on their project when another student, Owen, who has finished his dog pen, comes to look at their work.

Owen: Did you guys see ours?

Alexi: Yeah, yours is awesome. Did yours make it through the tests?

Owen: Not yet.

Mary: How are you guys testing it?

Stella: Um, over there. I don't know what she's going (pointing towards Ms. C.).

Mary: How do you think you'd want to test it?

Alexi: I think she's gonna take, like, a little wind-up toy, and it's just gonna walk around and it can't, your thing can't fall over.

Stella: Well this is felt (referring to a soft cloth), so I don't even know if it would be able to walk. But the felt is good, cause then it's soft.

The interaction between Stella and Owen evidences competing expectations for the design task. The “classroom” expectations involve passing the test with the wind-up toy; the client-focused expectations involve optimizing a design for Marty and Shiloh that makes sense in the story context. When Alexi asks Owen if his dog pen “made it through the tests,” she shows an awareness that their projects will be tested when they are done, that Ms. C. is “doing” the test, and that her design may be compared to the other students’ designs based on their relative success on the test. When pressed on what the test involves, Stella reacts dismissively: she gestures to the other side of the classroom, but quickly resumes her focus on constructing, biting her lip as she figures out how to attach the roof. She is clearly uncertain about the parameters of Ms. C.’s test, but does not seem fazed by this. Alexi then elaborates that the test involves an action that “she” (her teacher) will perform using a “wind-up toy” (representational Shiloh) to make sure the “thing can’t fall over” (dog pen stays upright). And, when Stella notices a feature of their design that might perform badly in that test — the felt that they are using as a rug for Shiloh may prevent the wind-up toy from moving during the test — she keeps it anyway, asserting that it is “good” for her client because it is soft.

In a classroom framing, the test likely adheres to students’ expectations for classroom occurrences in which a teacher evaluates their work. For the girls, “test” cues up just that: a pro-forma event that is disconnected from the story context and their goals. In this event, their teacher performs an action, Shiloh is a “wind up toy,” and their dog pen is a “thing.” Although they recognize that other students may be prioritizing the test, Stella and Alexi remain anchored in the story context, as evidenced in Stella's comment in the last line. Her explicit prioritization of Shiloh's comfort over classroom testing criteria suggests that she is aware of the competing sets of expectations but committed to her own.

Evaluating for the Client (Day Three)

On Day Three, all of the students take turns presenting and testing their designs. Ms. C. announces that the dog pen test is two parts: (1) a "small dog" test, which involves letting a small wind-up toy scurry about inside the pen for thirty seconds without escaping, and (2) a "big dog" test, which involves winding up two bigger toy cars (to represent big dogs) and letting them crash into the sides of the pen. During Stella and Alexi's presentation, they highlight meaningful features of their design, elaborating on how the tunnel will function as an escape route in case the antagonists of the story come after Shiloh. When they are ready to test, Ms. C. suggests that the first test should be for the small dog to slide down the secret tunnel part of the design. The students are gathered around Stella and Alexi's design to observe, hoping to see the small dog emerge from the bottom of the tunnel.

Students: He's at the bottom! ("He" refers to Shiloh and/or the toy).

Ms. C.: Oh, he came out! All right, so the small dog was able to go through the tube (referring to the tunnel). Why might it be tricky to test going *up* the tube?

Alexi: (without pausing) He (referring to Shiloh) doesn't go up the tube because Marty lives on the bottom of the hill and Shiloh's pen is on a hill. So he would just like (gestures motion to demonstrate Shiloh's path down the tunnel), Marty would walk him up the hill.

Ms. C.: Okay, so he's not expected to go back up the tube. He's expected to start at the top and go all the way down.

During the test, Ms. C. raises the question of whether using the toy would be appropriate to find out whether the dog could go up the tunnel. For Alexi, though, the question is moot. She responds by describing how the design works in the story setting, insinuating that there is no reason to test the small dog going up the tube because that is not how the tunnel is designed to function. Rather than adapting their framing to incorporate the classroom expectations, which could mean changing their design based on their teacher's concerns rather than Shiloh's needs, Stella and Alexi persist in attending to their clients' needs and adhering to the constraints of the design context.

Framing Dynamics

Like engineers, Stella and Alexi were continually reflecting on and responding to their clients' needs within the context of the story, reasoning about and negotiating decision criteria, and iterating as needed to develop an optimal design. What's more, they maintained attention to their clients even when confronted with competing sets of expectations for what they should be doing in this task. We see evidence of their stability in the data: when Ms. C. praises their use of "measurement," they acknowledge her comment, but continue working on their design; when testing parameters come up in conversation, the girls react dismissively and prioritize Shiloh's needs; when presenting, they do not adapt their design to accommodate their teacher's or classmates' comments, instead maintaining the evaluation criteria of the story setting.

Stella and Alexi's framing, however, was not a common occurrence across groups in the classroom. In other instances, students' sense of the task dynamically shifted as they interacted with other students, their teacher, and building materials or artifacts. To show the contextual sensitivity of students' framing, we describe a brief episode in which a group of three boys shift in their framing to prioritize classroom expectations.

Classroom framing. Jack, Cooper, and Thomas' early design discussions involved reasoning and making decisions that were based on "keeping Shiloh safe," and ensuring access to sunlight so Shiloh "doesn't feel trapped." Like Stella and Alexi, they were taking the perspective of their client, articulating implicit criteria, and evaluating it based on meeting those criteria. When presenting, however, the boys highlight different aspects of their design thinking as they ascertain, from the teacher's feedback, which is the information that is valued. In the following, Jack responds to Ms. C.'s prompt to reflect on what they would do differently next time.

Jack: Well, I think that we would probably make this (pointing to the door) more secure, and probably make this more like inside, so it like, more, what is (it) called? Like, more stabilized.

Ms. C.: Okay, using some really good vocabulary. I'm hearing *reinforce, stabilize, secure*.

Ms. C then gives the other students an opportunity to ask questions. One girl asks them why they thought to do “that kind of design.” When Jack responds that he just thought of making a rectangle instead of a circle because it would be safer, Ms. C. asks the boys about their choice of shape, as shown in the following.

Ms. C.: Why do you think rectangle versus a circle?

Jack: Because, um, well, a rectangle would keep him in.

Ms. C.: You don't think a circle would?

Jack: It might, but, um, a circle we just thought of, and then (we) were like, a rectangle, what about that? And so, we all had circles and he (pointing to Thomas) had a rhombus.

Ms. C.: I like the geometric terms we're using!

Thomas: I had a hexagon!

Jack initially reflects that their redesign would involve making it more “secure,” and recalling a new word, more “stabilized.” Ms. C. then commends him for his use of “good vocabulary.” Shortly after, when another student then asks the boys why they thought to do “that kind of design,” Jack describes that the rectangle shape of the dog pen was a determining factor in making it “safer.” When Ms. C. asks them if they considered a circle, the boys tip into a slightly different sort of activity. In this, they showcase their inventory of geometric terms[7], including “rhombus,” “square,” and “hexagon,” which they rightfully expected Ms. C. would appreciate. They appear less concerned about Shiloh’s safety and comfort, opting instead to share what they believe is valued, or counts, in a classroom evaluation.

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[7] Correspondence with Ms. C. describes her coverage of Everyday Math Unit in previous weeks.

For Jack, Cooper, and Thomas, forming a sense of the task involved attending to what was socially valued in their immediate classroom context, i.e., knowledge of vocabulary. Their framing of the activity, in that moment, evolved to incorporate their classroom expectations, influencing their choice of design features to highlight recognized words. In this, the students swiftly shift from evaluating their design to "answer-making" for their teacher (Hutchison & Hammer, 2010). The dynamics of student framing in engineering design align with other classroom-based accounts, in which students' ways of thinking are influenced by their interpretation of the task (Seigler, 1996), may shift within a single conversation (Hammer, 2004), and continually interact with social, conceptual, and epistemological aspects of discourse (Scherr & Hammer, 2009).

Stable beginnings in engineering. Our initial motivation to study this case was to examine Stella's and Alexi's abilities to reason and act as engineers. In early analyses, we examined how they spontaneously planned by considering multiple aspects of the design context and their clients' needs, and generated appropriate scales to ensure accuracy in a "real life" context. In accounting for social and physical dimensions, they seemed to tacitly recognize that "design does not take place for its own sake or in isolation, but rather is directed at a practical set of goals intended to serve human beings" (Vincenti, 1990, p. 6). Much like engineers, the girls demonstrated "design thinking," making informed assumptions about the problem situation (Adams & Atman, 2000), identifying and stating user needs, (Bursic & Atman, 1997, p. 66), and considering outcomes of hypothetical situations (Dym et al., 2005).

As we continued to study Stella and Alexi, we became more interested in their framing of what they were doing, itself an aspect of their nascent engineering. Like engineers, Stella and Alexi were continually reflecting on and responding to their clients' needs within the context of the story, in contrast to some other groups that evidently framed what they were doing more directly in terms of their own needs within the context of the classroom. Stella and Alexi's stability in framing the task as engineering for their fictional clients allowed them to purposefully navigate a design process. To co-construct their design idea, for example, Stella and Alexi requested graph paper and used it draw a detailed plan view of the dog pen. To specify dimensions, they generated a scale based on their assumptions of the client's needs, and when evaluating their design, they prioritized criteria according to Marty's and Shiloh's safety and comfort. They girls did not "Ask" about their clients because it was listed in a sequence before "Plan"; they tacitly responded to an implicit "Ask" by drawing inferences from the story and making assumptions regarding their clients' needs in service of designing a solution. Similarly, they did not evaluate their design based on a test that did not make sense to them; they evaluated it based on how it is supposed to function in a design setting.

In contrast to Stella and Alexi, other groups in the class were less stable in their framing, shifting in response to classroom cues. Jack, Cooper, and Thomas, for example, discussed their initial design decisions based on "keeping Shiloh safe," and ensuring access to sunlight so Shiloh "doesn't feel trapped," evidence of framing comparable to Stella's and Alexi's. Later, when presenting their design to their teacher, the boys made a point of using terms from geometry, including "rhombus," "square," and "hexagon," which they rightfully expected Ms. C. would appreciate. In another instance, a pair of girls incorporated LEGO figurines as "body guards" and pipe cleaners as "laser beams" to protect Shiloh. Because their initial design sketch did not include these imagined features, we suspect the girls' interest in craft materials triggered a shift in their framing away from the situation of the story. That is, they adjusted their framing of what they were doing, essentially shifting the genre of the story as written, to include elements of fantasy or science fiction[8].

To summarize, many of the students' framing of the Novel Engineering task dynamically evolved as they responded to classroom prompts, interactions with other students, or materials in the classroom. Stella and Alexi, however, remained stable in their focus on designing for their fictional clients, within the context of the story, even in potentially pivotal moments.

Their stability has piqued our interest and sparked a related research question: *What was it about their framing that enabled them to be stable*? Based on this analysis, our conjecture is that Stella's and Alexi's stability in this task came in part from their investment in the story, including their caring for the characters and their problem. We see evidence of the story holding their attention in their responses to questions about their activity, with references to details about the situation, such as Marty wanting to be Shiloh's owner, as well as signs of their imagining aspects of the situation not explicitly in the story, such as how their

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[8] Of course, Stella's and Alexi's design was also unrealistic—it would be quite difficult to dig that tunnel! Our claim is that imagining a tunnel is much closer to the story context than imagining bodyguards and lasers.

system might need to let Marty's family in, that Marty might need to get in the tunnel himself, or that the real need for the tunnel would be to escape from the pen to Marty's room if endangered. In this they demonstrate *design empathy* (Kouprie & Visser, 2009), an understanding of and concern for their clients, ensuring that Marty and Shiloh will have access to each other and that Shiloh's pen will provide safety, comfort, and security. By imaginatively projecting themselves into Marty's and Shiloh's situations (Koskinen & Battarbee, 2003), Stella and Alexi are able to deeply discern their clients' circumstances and perspectives (Battarbee, 2004), and to design a solution to best meet their needs.

While the importance of empathy in design is well recognized (Batterbee & Koskinen, 2005; Brown, 2009), many researchers have noted that it is often lacking in the design process (Fulton Suri, 2003; Mattelmaki & Batterbee, 2002), and have developed a number of tools and techniques to enhance designers' empathy (Kouprie et al., 2009). In this case of children engaging engineering design, however, we see the opposite: Stella and Alexi's ability to empathize not only informs their design decisions, it supports and sustains their framing of the task as engineers.

Conclusion

In this study, we showed that elementary students have abilities to reason and act as beginning engineers, and that they may enact those abilities when their understanding of the experience calls for it. For Stella and Alexi, developing an optimal solution for Marty and Shiloh was a central objective; their actions of inferring design criteria and constraints, making informed assumptions and estimates, co-constructing scaled representations, and defining evaluation criteria served a purpose in helping them achieve this objective. The girls did not treat the activity as a well-defined task or try to follow design steps in a linear order, as the literature claims "beginning" engineers do (Crismond & Adams, 2012); instead, they explored the problem to understand clients and iteratively navigated their own design process to meet their clients' needs. We argued that the girls' framing of the activity involved their engagement in engineering design, and that the abilities they demonstrated in pursuit of a solution were *productive beginnings* in engineering design.

This case study is part of a larger project to understand students' framing in engineering. The findings we present here suggest that when students' framings have them acting as constructors and evaluators of their design, they may purposefully navigate an engineering design process in pursuit of an optimal solution. From this and other observations and analyses, we suggest that student framing should be a central target in engineering education research and practice. By attending to student framing in research, we may understand not only students' engineering abilities, but also their reasons for enacting those abilities. Moreover, we may be better equipped to foster and cultivate productive framing during engineering activities in practice, providing students with opportunities to design for clients and to interact with multidimensional problem situations. Our hope is that as students gain experience in framing as engineers, they may strengthen their abilities to navigate complex design situations, such that their engineering “ways of knowing” become “tacit, spontaneous, and automatic” (Schön, 1983, p. 60).

Implications

These complexities in framing dynamics give rise to many questions for instruction and warrant further research in how students make sense of open-ended design activities. For instruction, we consider how teachers’ lesson structures and responses to students’ design ideas may play a pivotal role in their framing. Teachers must make choices regarding how open-ended to make the design activity, the nature of design constraints, available materials, whether students’ designs will all be tested, and so on. These choices may largely influence how students take up the design task: in highly structured tasks, students may be more inclined to frame the design task as a “school” activity; however, in completely open-ended design tasks, students may deviate from the design situation to create representations of fantastical solutions (see Chapter 5). We argue that these complexities warrant deeper research, particularly for recognizing engineering design abilities students bring to bear in classroom settings, and for understanding how instruction can be designed to tap into and nurture students’ abilities.

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Chapter 5: Pretend Roofs and Laser Beams: The role of materials and artifacts in students' framings of a Novel Engineering design experience

This paper is part of larger study to examine the dynamics of elementary students' engagement in integrated engineering and literacy design activities. In this study, we illuminate the complexities that may arise as elementary students engage in open-ended design activities. In particular, we examine how students' interactions with materials and artifacts as they are constructing engineering representations (e.g., sketches, models) involve and are evidence of their *framing* of the activity (Goffman, 1974). Understanding the dynamics of student framing in engineering design, particularly the pivotal role that representations play, is of central importance in engineering education: while open-endedness may enable students to engage in rich and complex reasoning in engineering design, it may also support their engagement in other kinds of activities, such as make-believe games, that do not necessitate engineering reasoning. In this empirical case study, we focus on two groups of fourth grade students who are participating in an integrated engineering and literacy activity. We show how each group's framing of the task evolves dynamically and uniquely as they interact with material objects, and how their locally stable or shifting framings influence their engagement in engineering design.

Pretend Roofs and Laser Beams: The role of materials and artifacts in students' framings of a Novel Engineering design experience

Introduction

Recent publications at the federal level, including position statements (National Academy of Engineering, 2009), frameworks (National Research Council (NRC), 2012), standards (Next Generation Science Standards, 2013), and assessment criteria (National Assessment of Education Progress, 2014), have brought about nationwide initiatives and state standards that incorporate engineering design into K-12 education (Carr, Bennett, & Strobel, 2012). These initiatives are driven by a central mission: to prepare rising engineers to "undertake more complex engineering design projects related to major global, national, or local issues" (NRC, 2012, p. 71). As researchers have noted, students need to be able to solve complex, multidimensional problems in the real world, but they must also have opportunities to do this in classroom environments (Jonassen, Strobel, & Lee, 2006). Attending to this mission requires a shift in the status quo: well-defined engineering problems must be replaced by those that more closely reflect professional engineering – i.e., problems that are open-ended, ill-defined, and rely on multiple forms of representation (Atman et al., 2007; Bucciarelli, 1996; Goel & Pirolli, 1992; Johri & Olds, 2011; Jonassen, Strobel, & Lee, 2006; Schön, 1987). While the former may have students memorizing prescriptive arrangements to arrive at "right" solutions (Jonassen, 1997), the latter calls them to navigate ambiguous design situations, coordinate conflicting goals, and account for unanticipated constraints (Jonassen et al., 2006).

In elementary settings, open-ended design projects may engender new complexities; more specifically, an ambiguous design situation coupled with the representational nature of designing prototypes may lead to different interpretations of the task, some of which are more closely aligned with professional engineering practice than others. That is, while some students may understand the task as involving development of functional prototypes for a client, others may see it as an opportunity to create imaginative dioramas. To date, the engineering education community knows little about how children manage the complexity and ambiguity of open-ended design situations (Johri, Olds, & O'Connor, 2014). The majority of research in elementary engineering education aligns with current ways of teaching engineering; the foci include students' ideas *about* engineers and engineering, and knowledge *of* the design process. For instance, researchers have developed numerous assessment instruments to measure students' engineering design knowledge (Hsu, Cardella, & Purzer, 2012), conceptualizations about what engineering or technology is (Cunningham, Lachapelle, & Lindgren-Streicher, 2005), and what engineers do (Dyehouse, Weber, Kharchenko, Duncan, Strobel, & Diefes-Dux, 2011).

In this study, we delve deeper into the complexities that arise as elementary students engage in an open-ended design activity involving the integration of engineering and children's literature. In particular, we examine how students' constructions and uses of representations, specifically their interactions with classroom building materials (e.g., cardboard, paper, tape) and artifacts, influence their sense of the task.

For engineers in practice, representations[9] (e.g., sketches, models, prototypes) serve as the primary language of design (Dym, 1994), providing a medium to navigate uncertainty, to negotiate and align their perspectives and expertise, and to coevolve design ideas (Bucciarelli, 2002; Hall & Stevens, 1995; Lynch & Woolgad, 1990; Stevens, 2000; Stevens & Hall, 1998; Suchman, 1987). The flexibility of representational spaces and tools, such as drafting paper and computer models, supports fluidity in ideation and iteration, allowing engineers to analyze and evaluate ideas with respect to specific contexts. Numerous ethnographic accounts of engineers in practice support this notion: Hall and Stevens (1995) refer to "model spaces," encompassing sketches, computer models, and narratives, that allow engineers to coevolve design ideas; Bucciarelli (1988) introduces the term "object world" to identify "different worlds of technical specializations with their own dialects," that engineers bring to bear when representing solutions (p. 161); Henderson (1991) describes the "visual culture" of engineering design, suggesting that engineering drawings and sketches are the devices that socially organize the workers, the work process, and the concepts in engineering design.

In a similar way, representations play an integral role in students' learning in general, allowing them to interact with their own and peers' ideas as they make craft projects, illustrate stories, or reason about mathematics and science concepts

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[9] For the purpose of this study, we narrow the scope of *representations* to include visual artifacts, including inscriptions, sketches, and physical objects, specifically those that serve a symbolic function in that they come to stand for referents that are not immediately present (Cobb, 2004; Gibson, 1979; Ittelson, 1996; Kaput, 1998). We assume that the ways representations are used and the meanings they come to have are mutually constitutive and co-emerge in use (Cobb, 2002; van Oers, 2000). We also assume that artifacts do not need to be representational and may simply be objects.

(e.g., diSessa et al., 1991; Lehrer & Schauble, 2000, 2002; Piaget & Inhelder, 1966/1978). For students learning engineering, representations, including materials and artifacts[10], provide flexibility in their imagining, communicating, evaluating, and changing design ideas and concepts. However, in open-ended design activities, the conceptual flexibility afforded by representations may also affect students' sense of the activity, allowing them to flexibly adapt their interpretations of the design task. That is, students may tacitly assume the boundaries of a solution space are malleable, adjusting the criteria and constraints to reflect their shifting purposes and objectives. For example, students may select and use materials purposefully to construct and evaluate their design ideas for a specific client in one moment, but may quickly become more interested in the materials themselves, and expand their design solutions to encompass imaginative uses for materials. Students' local purposes, in this example, fluctuate as they interact with materials in the classroom: developing representations to evaluate optimal solutions for their clients morphs into making fantastical representations that are comprised of attractive materials. Understanding the dynamics of how students form a sense of engineering design tasks, particularly the pivotal role that representations play, is of central importance in engineering education: while open-endedness may enable students to engage in rich and complex reasoning in engineering design, it may also support their engagement in other kinds of activities, such as make-believe games, that do not necessitate engineering reasoning.

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[10] I use *artifacts* throughout this paper to refer to students' physical constructions, and *sketches* to refer to their drawings and inscriptions.

In this case study, we examine how fourth-grade students form a sense of an open-ended task, involving what they attend to, their objectives, and their commitment to rules or constraints in the activity, as they are constructing design representations. In one classroom, students' engineering designs took a variety of forms over the three days: some became equipped with pretend technologies (e.g., laser beams, video cameras, plasma TVs); others had functional features, such as doors and sturdy walls; many had both. We propose that the diversity in students' designs reflects not only differences in their solutions but is also evidence of fundamental differences in their assumptions and objectives for the task. We explore how students form this sense – that is, their *framing* of what is taking place (Goffman, 1974; Tannen, 1993), particularly with respect to knowledge and learning (Hammer, Elby, Scherr, & Redish, 2005; Redish, 2004). In our analysis of video data, we attend to local dynamics in student discourse and action to interpret student framing. We argue that students' interactions with materials and artifacts involve and inform their framing in engineering. Our aim in this effort is not to characterize the specific indicators or competencies in student learning, but to understand the complexities and idiosyncrasies of students' sense making as they frame an engineering design activity.

We begin by drawing from literature on representations from a disciplinary engineering perspective to shed light on the complex nature of representing in engineering design. These accounts provide a basis for understanding aspects of students' representing that reflect those of professional engineers. In particular, we focus on elucidating engineers' uses of materials and artifacts as representational tools and media within the process of design. We then draw from literature on elementary students' uses of representations, exposing some of the ambiguities that are inherent in acts of representing, and argue for attention to student framing during an ongoing activity. With a framing lens, we turn to a fourth grade classroom, focusing on two groups of students participating in an open-ended design activity. Each group demonstrates unique ways in which students' interactions with the materials and artifacts involve, inform, and are evidence of their framing of the activity. In considering these cases, we discuss the productive aspects of student framing and the implicit challenges that may arise.

Representing in Engineering Design Contexts

Accounts of professional engineers document engineers' representational practices – how they use tools, materials, and artifacts as representations in communicating and evolving design ideas (Hall & Stevens, 1995; Lynch & Woolgad, 1990; Stevens, 2000; Stevens & Hall, 1998; Suchman, 1987). There are two themes in engineering literature that are relevant to this study: first, the nature of representations in engineering, which are dynamic and flexible; and second, the ways engineers manage and exploit this flexibility in evolving design ideas. The conceptual flexibility of representations relates to the malleability and transience of design concepts; by using inscriptions, modeling programs, artifacts, and other media to represent ideas, engineers are able to fluidly communicate, adapt, and compare design alternatives in various spatial and narrative forms (Stevens, 2000). In collaborative environments, design features are subject to multiple perspectives and may change or evolve as engineers negotiate design parameters; engineers may look at the same object, but perceive it differently and in accord with a unique functional perspective (Bucciarelli, 1994).

The ways in which engineers see, orient to, and coordinate visual aspects in design is fundamentally shaped by their previous experiences, activities with other people, and culturally specific artifacts (Bucciarelli, 1994; Stevens & Hall, 1998). An inherent socio-material challenge for engineers is to manage the flexibility of representations, to bring their ideas and perceptions into alignment, and to establish coherence through communication and negotiation (Bucciarelli, 1994). Looking for coherence among divergent visions resonates with Stevens and Hall's (1998) notion of "disciplined perception." As Stevens and Hall (1998) point out, learning to "see" form in representations involves "disciplined perception," which refers to the ways that people in a discipline learn to see and interpret focal phenomena through tools and representations. This typically occurs when two or more individuals see different entities in the same representation, and then communicate, adjust, or shift perspectives to view, communicate, and align their ideas. In establishing a shared perspective, engineers are able to construct alternative designs and evaluate the qualitative and quantitative differences between these alternatives towards achieving an end goal of an optimal solution.

Representing in Elementary Classrooms

Students, like engineers, create, use, and interpret a variety of representations, such as drawings, books, and notations, on a daily basis. As they do so, students reason and enact different epistemic activities in service of local purposes, which may shift depending on what they think the task is about. Hall and Stevens (1995) illustrated the contextual sensitivity in students' representing in an *in situ* comparison of students' and engineers' representational practices. They found that the physical workspace (i.e., computer screen versus paper) mattered for the types of epistemic activities students engaged in: working on paper led some students out of the design activity to focus more on how they would be evaluated as students. For engineers, however, both workspaces were peripheral tools that enabled them to co-construct a design in a shared pursuit. Hall and Stevens (1995) attribute the fluctuations in students' representational practices to their *a priori* commitments to classroom evaluation criteria – students' ideas about "right" problems and "correct" solutions (p. 20), which students may foreground when positioned around a computer or desk. This finding, we believe, is not surprising: students' tacit understandings of a task, and their assumptions for how they will be evaluated on the task, matter for the types of reasoning and epistemic activities they engage in, and these may shift as students interact with materials, tools, and each other in classroom environments.

From a similar view, researchers have suggested that differences among students' representations are not indicators of varying abilities, but instead reflect differences in students' sense of the experience and the epistemic activities they see as being useful in that experience (Hall, 1996; Roth, 1996; Roth & McGinn, 1998). Our work builds on this view by suggesting that students' sense of the activity may shift and evolve as they are constructing and interacting with representations, specifically with materials and artifacts. Their interactions, in turn, may influence the epistemic activities and competencies they see as being relevant to the task. In the following, we discuss the construct of framing as a lens for understanding the complex dynamics of these interactions during classroom experiences.

Framing

We examine students' understandings of their local situation – their circumstantial aims and purposes within an experience – as evidence of and involving their framing of the activity. An individual's framing of a situation involves an active, ongoing response to the tacit question, "what is it that's going on here?" (Goffman, 1974, p. 8). Frames are cognitive structures of expectations, existing as "active, organized settings" (Bartlett, 1932, p. 201), that dynamically evolve to reflect and inform an individual's sense of an experience; "one's structures of expectation make interpretation possible, but in the process, they also reflect back on the perception of the world to justify that interpretation" (Tannen, 1993, p. 20-21). In framing a situation, an individual is tapping into previous patterns of experiences and interacting with them; the patterns themselves adjust to accommodate the new situation, continually influencing what an individual notices, the knowledge she accesses, and how the individual acts (Hammer, Elby, Scherr, & Redish, 2005).

In classroom settings, the ways students frame learning experiences have implications for how they think about knowledge and learning, navigate social situations, and engage in activities: students may frame a physics problem as an occasion to use rote formulas or as an opportunity for sense-making (Hutchinson & Hammer, 2010; Scherr & Hammer, 2009). Analogously, students may frame an engineering design task as an occasion to construct, analyze, and evaluate design solutions, an opportunity to tell stories or create dioramas, a time to play the "classroom game" (Hutchinson & Hammer, 2010; Lemke, 1990), or some combination of experiences. In this, they are drawing from previous experiences they perceive to be similar (e.g., storytelling, making things, show-and-tell), and adapting their expectations to reflect their current situation.

Methods

Data collection and selection. In our analysis, we focus on the moment-by-moment shifts in meanings that occur as students are learning in socially and materially rich settings. To account for subtle shifts and coherences in the flow of activity, we collect *in situ* video data during engineering activities. As previous researchers have noted (Derry et al., 2010; Jordan & Henderson, 1995), videos provide a medium for analyzing naturally occurring phenomena. During classroom activities, our research team sets up small, tripod-based cameras on randomly selected student groups, often with additional microphone units to capture sound adequately.

Our primary data sources include direct observations and videotapes of design-related activity, field notes, and students' engineering artifacts. Our selection of data is based on our analysis of student discourse, including their physical interactions with objects and materials. For this study, we present cases that exemplify the complex dynamics of students' framings occurring as they interact with material and artifacts in the classroom. In other work, we analyze a case of stability, focusing on a pair of students, who maintain attention to their fictional clients throughout their design process; like engineers, they navigate the flexible representational space, analyzing, evaluating, and communicating their design idea, but stay focused in their objective for the task (McCormick & Hammer, 2014). Our focus here is on two groups of students who are less stable in their framing, with particular attention to moments in which they shift or adapt their framing of the activity. The presented cases are not intended to be a comprehensive survey of framing dynamics in open-ended design activities, but rather are intended to shed light on the dynamics of student framing during engineering design activities.

Data analysis. In our analysis of video data, we draw on tools from discourse (Gee, 1999; Goodwin, 2000, 2007; Scherr & Hammer, 2009) and interactional analyses (Jordan & Henderson, 1995) with attention to both verbal and non-verbal aspects of the data to interpret students' framing of the activity throughout their design process (McCormick & Hammer, 2014; Tannen, 1993). Our analytic foci include students' attention to, interactions with, and reasoning about the uses of materials as they develop representations (i.e., sketches and models). In particular, we pay close attention to moments when students transition in their uses of materials and objects in their designs. From the data, we interpret student framing in local moments by examining their orientations to the design objectives, clients, and context. We then examine and compare students' reasoning and actions occurring within those framings to disciplinary engineers' to understand productive aspects of student framing.

Research setting. This study is part of the *Novel Engineering* project that is funded by National Science Foundation at Tufts University. In a Novel Engineering activity, students design and construct engineering solutions for characters in the books they are reading. Participating teachers from urban, suburban, and rural schools attend approximately forty hours of professional development per school year at Tufts University and work with researchers to develop lessons and implementation strategies. This case study is drawn from a fourth grade classroom in a rural town in Massachusetts, about forty miles from Boston. The teacher, Ms. C., a first-year participating teacher on the Novel Engineering project, decided to do an activity based on the book *Shiloh* (Naylor, 1991), a novel that takes place in West Virginia in the 1960s. The characters in the book are an eleven-year-old boy named Marty and a small beagle named Shiloh. The students' task was to engineer "desk size" dog pens using an assortment of craft materials (e.g., cardboard, paper, glue, pipe-cleaners, popsicle sticks) to keep Shiloh safe from antagonists in the story, including the dog's owner and a German Shepard.

Ms. C. planned the dog pen task because she wanted all of her students to be working on the same engineering problem for their first project and seemed comfortable with the level of specificity and testability of the engineering design project. Ms. C. had read *Shiloh* aloud to the class over the two weeks prior to the hands-on engineering activity. She structured the hands-on engineering component over consecutive three days for about ninety minutes per day: the first day involved discussing the major problems in the book and starting individual plans; the second day involved working with classmates on design plans and building; the third day involved finishing designs, testing, and presenting to the class.

Analysis

In the following, we highlight different ways in which students' interactions with materials and artifacts involved and informed their framing of the design experience. We illustrate two brief cases of two groups in the same class to provide a glimpse of the varying dynamics of student framing, particularly those that involve students' perceptions and interactions with objects and their artifacts. We begin by showing brief episodes of Jack, Cooper, and Thomas during their design process, and then transition to showing episodes of Katie and Maria. In both sets of data, we highlight pivotal moments in which students' perceptions and interactions with the materials and their artifact influences their framing of the task.

Ms. C.'s Design Requirements

During a group discussion on Day One, Ms. C. introduced the engineering task of building a new dog pen for Shiloh. She suggested that each student sketch a design drawing individually before finding a partner to work on a group design. She also announced that they would have an opportunity to build their dog pens and would be using mostly classroom materials (e.g., cardboard, scissors, glue, etc.).

At the start of Day Two, Ms. C. began the class with a group discussion to summarize design requirements. Students learned that their constructions must "fit on top of our desk, the test must be able to fit inside," and it has to be "some sort of enclosure." Like many engineering design problems, the task was open-ended and vague in several respects: the students were to design a solution that is meant for their fictional clients, but the design was to be constructed from classroom materials, fit on their desks, and would need to pass some sort of test.

Jack, Cooper, and Thomas

Three boys, Jack, Cooper, and Thomas, spent much of the first day discussing the elements of their design (see Figure 5-1). Each of them had worked on his own design sketch, and then they worked together to combine ideas for their shared design[11].

This excerpt takes place during Day Two, approximately twenty minutes after starting the activity. In this excerpt, the boys have gathered materials, such as cardboard boxes, tape, and tubes and are beginning to construct their dog pen. In the following, a researcher, Jess, asks them about the features of their design.

18:09 Jack: But like, he (referring to Shiloh) wants to have a see-through roof, so we're trying to find out like what's see-through.

Jess: He wants to have a see-through roof?

Jack: So he can see the sky and stuff.

Jess: Oh, yeah?

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[11] Based on teacher description of previous class period; data was not collected during their initial drafting of designs.

Jack: So Shiloh doesn't feel, like, trapped, and so it (referring to German Shepherd) can't get in. So we were thinking of leaving it (without a roof) and put the fence really high.

A few moments later, after the researcher has left, Jack, Cooper, and Thomas reflect on the dimensions and appropriate scaling of their design. They are holding up the cardboard sheets perpendicular to their desks.

Jack: But guys, it (a “fence”) needs to be higher.

Thomas: A dog can't get that high.

Cooper: A dog can't jump like twenty feet high in the air!

Jack: No, but a dog can jump this high (gesturing a distance above the dog pen).

Cooper: That's pretty high…

Thomas: Yeah, but we’re pretending this is pretty high.

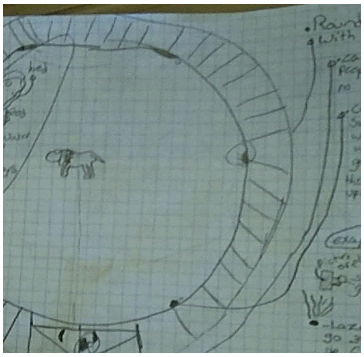

Figure 5-1: Jack, Cooper, and Thomas’ design sketch

In this initial part of their work, Jack, Cooper, and Thomas are negotiating aspects of their design based on how it will serve their fictional client’s (Shiloh) needs. In reasoning about whether to have a roof or fence, they infer what Shiloh might need for both comfort and safety: Jack describes that he will need to “see the sky and stuff' so he doesn't feel trapped, but will still need protection from other dangers (i.e., the German Shepard in the story who attacks Shiloh). They make qualitative judgments regarding the necessary height of the walls to prevent a big dog from jumping into the pen (in the case of not having a roof). Making these judgments, however, requires several mathematical steps: they tacitly generate a scaling factor based on the real life – to – desk conversion, apply that scaling factor to convert estimates of how high a dog can jump, and then compare the converted dog-jump height to the piece of cardboard Thomas is holding on the desk. When they have slightly different estimates, the boys clarify two implicit assumptions: Jack states his assumed jumping height for dogs, and Thomas affirms that they are pretending the piece of cardboard is "pretty high."

At this early stage, the boys' interactions with materials, such as the cardboard wall, and their reasoning about their artifact involve and are evidence of their framing of the task. They draw from their own experiences involving dogs, the story, and using mathematical relationships to bring their ideas regarding the design solution to bear. In doing so, they exploit the flexibility of representational space to freely discuss ideas without making definite decisions, and to negotiate particular design decisions. The materials (in this instance, cardboard) provide an external medium for them to make assumptions regarding dogs and scaling factors explicit, and to align their framings of their design objective. Their exchange regarding the height of the fence reflects disciplined perception in engineering contexts. Stevens and Hall (1998) describe patterns of disciplined perception as unfolding in the following sequence: two or more individuals recognize an intersubjective disparity, an announcement is made concerning the disparity, an individual initiates a directive "look at this way" perspectival shift, followed by an embodied course of action through which the initiator coordinates aspects of views to animate "this way" (p. 141). Here, Cooper recognizes and communicates a disparity in their estimates ("a dog can't jump like twenty feet high in the air!"). Jack then articulates the realistic basis of their assumption ("a dog can jump this high"), and Thomas clarifies that they are applying a large scaling factor ("we're pretending this is pretty high") while holding the paper-size piece of cardboard perpendicular to the desk. In aligning their perceptions, the boys then continue to work on the design together.

During the thirty minutes following this first episode, the boys work together on co-constructing a scaled dog pen. At one point, they recognize that the vertical sides are not staying propped upright and decide to start over with a more stable cardboard base. To ensure lateral stability, they add a piece of cardboard to cover half of the top, creating a partially-roofed dog pen. Unsure of whether to cover the other part of the roof (for full enclosure) or to leave it open, Jack asks Jess what they should do.

> Jack: So like should we leave a little hole right here (pointing to an open space without cardboard on their artifact) so people can look in?
>
> Cooper: I think we should.
>
> Jess: Which people are you thinking about?
>
> Jack: Like if, say, Ms. C. or someone wants to like look in.
>
> Jess: Oh, like if we want to look in and see what's in there.

Jack: Yeah.

Jess: Oh, I see, um, and so you think it'd be a good idea to have it, have it be open so people could see what you guys have done inside?

Jack: Yeah.

Jess: Oh, okay. That sounds like a good idea.

Jack: Okay.

Cooper: I'm really thinking about the inside, because Shiloh needs stuff to play with inside.

Jack: And we have a door that opens and closes and we have a little eye hole.

Cooper: It has a little hole...

Jess: Oh, cool.

Cooper: Look down, look down. See that little hole (pointing to eye hole)? Then rain could get in. Let's pretend we have a roof there.

Jess: You want to have a roof there?

Thomas: Yeah.

Cooper: No, let's *pretend*.

Jess: Let's pretend we have a roof there. Why do you think it needs a roof?

Cooper: Because of rain.

Jess: Oh, cause of rain, okay.

Cooper: Not many people are thinking about that.

Jess: Yeah, not a lot of people are thinking about that, are they?

> Cooper: And what if the dog (referring to a bigger dog that attacks Shiloh in story) has sharp claws and stabs them in (to the side of the dog pen) and "rar" (growling sounds) or something (motions the dog jumping in from top)?
>
> Jess: Oh, so to protect him from on top.
>
> Thomas: He would fall...
>
> Cooper: No, cause look, I don't know.
>
> Jack: Thomas, Cooper! (Holding a plastic bag in the air.)
>
> Thomas: Yeah, a bag! We can cover it with a bag!
>
> Cooper: A bag, like a light bag that people could see through.
>
> Thomas: That's smart, smart idea.
>
> (Jack places the clear plastic over the open space of the roof.)
>
> Cooper: Now you can still see in.
>
> Jack: Yep, you still see in.

As the boys are constructing their dog pen model, they pause before placing a roof across the entire top of their dog pen and reconsider. They recognize that there are potential advantages of not having a full roof: by leaving it partially open, their teacher, researchers, and classmates will be able to see the interior design work. In considering trade-offs, the boys are not only thinking about the structural advantages and disadvantages, they are reasoning about what “counts” as optimal in both the context of Shiloh and their immediate classroom context. Paradoxically, what counts in their immediate classroom context – the thought and effort they put into designing the inside – may be lost in meeting their original design criteria of keeping Shiloh safe. To clarify the objective of the task, Jack seeks guidance from an authority figure, a researcher in the classroom, asking if they should leave an opening “in case Ms. C. wants to look in.”

Jack’s sudden awareness marks a subtle shift in his thinking about Shiloh as being the primary client to considering the other evaluators, such as their teacher, peers, and the researchers. Cooper counters Jack’s suggestion and draws them back to the story context, announcing that he is “really thinking about the inside because Shiloh needs stuff to play with,” and points out the possibility of Shiloh getting rained on if they leave the roof open. Cooper then comes up with a design alternative that embodies both objectives: a pretend roof, which will allow his teachers and others to see in *and* will show that they have considered all of Shiloh’s needs. Proud that he has considered and accounted for the possibility of rain, Cooper then follows up with “Not many other people are thinking about that,” evidencing awareness that their design will be evaluated relative to their classmates’. Turning back to the story context, Cooper then suggests that another advantage of the roof is that it will protect Shiloh from the other dog. Seconds later, Jack holds up a clear plastic bag and calls out to Thomas and Cooper. Without any hesitation or need for explanation, Thomas and Cooper both recognize the bag as an alternative roof-building material and excitedly approve. The plastic bag meets the same criteria as the pretend roof (i.e., visually accessible inside, protection from top), but more effectively functions as a physical barrier and does not require others to imagine the pretend roof.

In this episode, the boys fluctuate in their framing as they interpret the role of their artifact within the local context of the classroom environment, including their teacher, the researchers, and the materials that are available. While their initial design had a roof for Shiloh, Jack reconsiders the roof, realizing that it might prevent his teacher, or others in the classroom, from seeing the inside. As the boys interact with their artifact, the materials at hand, and others in the classroom, their understandings of the task objectives shift between and combines aspects of classroom and story contexts. These dynamics are evident in their reasoning about the advantages and disadvantages of roof alternatives; Cooper, in particular, toggles back and forth, describing pros and cons of having a roof. Cooper's idea for a pretend roof is evidence that he is considering and negotiating sets of criteria simultaneously in *both* contexts. As he interacts with the artifact itself and others in the classroom, he draws from expectations, possibly involving pretending, making things, and being a student in a classroom. In this moment, his framing of the task emerges as a combination of engineering (solving a problem), classroom (being evaluated), and pretending (imagining what is not available). It is not clear whether the other boys share this framing until Jack holds up a clear plastic bag; their collective excitement about finding a material that will provide a physical ceiling barrier, while still allowing people to see the inside, suggests that they have the same design criteria.

The boys' perceptions of their artifact prompted them to reconsider not only the elements of the design, but their overarching purpose and objectives for the task itself – their primary clients and the criteria that are important to those clients. Jack, Cooper, and Thomas' reasoning reflects heterogeneous aspects of engineering design, which involve intricate arrangements and alignments of social and material elements. They consider multiple perspectives, integrating the social and material relations, to convey their design ideas (Law, 1987; Suchman, 1987, 2000). In their case, Jack, Cooper, and Thomas were considering not only the user (Shiloh), but how their design would be perceived by their immediate clients in the classroom environment, including their teacher, classmates, and researchers in the room. Engineers, too, must make these kinds of social considerations. Along with the design of plans, engineers are frequently engaged with the creation of what they term "artwork"; that is, renderings of proposed designs created not as instructions for building but as illustrations for communicating (Suchman, 2000, p. 318). While on the surface the students appear to be tinkering with materials, and at times, pretending, their work is similar to professionals' "ad hoc artifact making," an essential mode of thinking through design that "allows for the kind of experimentation and innovative thinking that designing requires" (Bucciarelli, 1994, p. 228).

Over the course of their design, the boys' interactions with materials and artifacts involved, informed, and were evidence of their evolving understandings of the design task. Their early interactions with available materials, such as cardboard, allowed them to negotiate their purpose and use of representations, specifically a shared understanding of the scale for making a "desk size" dog pen. Later, their perception of their partially-constructed artifact prompted a reconsideration of their design criteria with respect to multiple clients. While their framing shifted in this moment to include classroom expectations, their artifact maintained stable representational associations – specific materials were linked to design features in the story setting. Their subsequent interactions with materials (i.e., plastic as a roof material) then stabilize their framing, allowing them to test and communicate a design solution that is both functional and representational.

Katie and Maria

In the same classroom, Katie and Maria are working on their dog pen design. Their sketch (see Figure 5-2) shows Shiloh's pen to be orthogonally positioned and approximately equal in size to Marty's house. Shiloh's pen is connected to Marty's house by a tunnel; it is not clear if they purposefully oriented their sketch in such a way to show a tunnel, or if the orientation of the connecting path with respect to Marty's house spawned the idea of a tunnel. On their sketch, Katie and Maria have filled the interior of Shiloh's pen with numerous features, many of which are technologically advanced designs for human needs, such as a TV, a large bed, and a full bathroom.

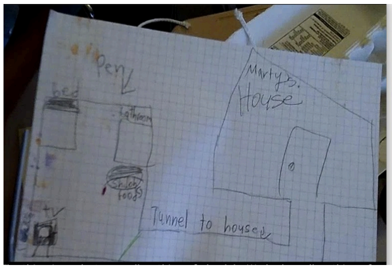

Figure 5-2: Katie and Maria's sketch

Figure 5-3: Katie and Maria's artifact

Approximately twenty minutes into the activity, Katie notices that the building materials have become available in the classroom, and she and Maria rush to pick out cardboard, felt, pipe-cleaners, egg cartons, LEGO parts, and Play-Doh for building their dog pen. They spread out all of the materials across their desks and begin cutting cardboard and manipulating pipe-cleaners and LEGOs. In the following excerpt, Katie is holding a cylindrical cardboard tube to her eye, when Ms. C. approaches to ask about their design.

Ms. C.: So what's this going to be (referring to the cardboard cylinder)?

Katie: I think it's gonna be a little video camera (looking through the object).

Ms. C.: Oh, neat.

Katie: I can't see through the video camera (manipulating cardboard).

Maria: I'll get some tape...

Katie: (Holding it up to her eye) I can see through it now!

Approximately twenty minutes after this first excerpt, a researcher asks Katie about their design, and she responds as follows (see Figure 5-3).

38:30 Katie: These are laser beams (holding pipe cleaners) that hit across the room. So if anyone mean tries to get Shiloh or breaks down the door, they get zapped by the laser beam. And like if someone, if someone just randomly comes running for Shiloh, trying to go through the doggie door, this (pointing to jagged cardboard piece that is protruding from wall) just hits them. And also, there’s a paw scan somewhere (looking around). I can make that out of LEGO.

Shortly after Katie’s description, Maria discovers a LEGO figurine and excitedly adds that “bodyguards” will also be there to protect Shiloh.

For the girls, the available materials play a role in their framing of the experience, allowing them to draw from other experiences involving representing, such as make-believe and storytelling. Katie's brief interaction with her teacher affirms their uses of materials. As Katie is manipulating the cardboard material, she holds a tube shape up to her eye and peers through, suggesting "I *think* it's going to be a video camera." She expresses hesitancy in her idea to her teacher, couching her suggestion as "I think"; it is unclear whether she is uncertain of the acceptability of a "video camera" in Shiloh's dog pen, or of the video camera functioning properly (i.e., providing an unobstructed view). In the former possibility, Katie seems to be checking her expectations with her teacher: she subtly proposes an alternate framing involving an imagined design space that is not bound by the reality of the story or functionality in the immediate classroom. When Ms. C. acknowledges and supports Katie's camera idea ("Oh neat"), she legitimizes the make-believe technology as being an acceptable feature of the design and use of materials, allowing Katie to expand more freely on their design to incorporate imaginative meanings for unique materials and objects. For example, upon finding pipe cleaners and laying them across the bottom of their model, Katie excitedly describes the "laser beams that hit across the room" to zap intruders, adding technologically-advanced protection mechanisms to their design idea. Katie then describes that the jagged cardboard edge protruding from their model (which appears incidental, rather than intentional), will injure intruders and finds a LEGO brick to stand for a "paw scan" for Shiloh.

As they discover and interact with objects from the supply of materials, they continue to add imaginative features that do not adhere in time or place to the context of the problem situation. The girls' framing emerges in the dynamics of their to-and-fro movement between identifying objects of interest and generating meanings that fit within their expectations of viable design solutions. At times, their attribution of meaning is driven by their perceptions and interactions with objects (jagged edge becomes form of protection or weapon); while at others, their design ideas create a need for materials to act as referents for those ideas (needing to find a LEGO for a paw scan).

When students are presenting their ideas to each other on the last day, Katie and Maria describe their dog pen representation, highlighting specific features of their design concept, such as the “laser beams,” “video camera,” “paw scanner,” and “bodyguards.” In the following, Katie begins to describe advantages of their dog pen representation as an object itself by describing its size in relation to other students’ dog pen models.

> Katie: It's small compared to everyone else's. But, like, smaller's kind of better because it's portable.
>
> Ms. C.: So, *portable* for you, for your project, or do you mean portable for Marty as well? Would he be able to pick it up and go?
>
> Maria: Yeah, Marty would be able to pick it up.
>
> Student: But wouldn't that…?
>
> (Many students raise hands and chime in with questioning voices.)
>
> Katie: Like, it's light, so Marty, if there's any problem, and for some reason Marty can't pull it down,
>
> Katie: He can just pull like these secret flaps.

Maria: Yeah, like we're going to attach a little something there so Marty can pull it up.

Ms. C.: Then again, this is a much smaller version of what it would actually be, right?

Maria: Yeah, like a mini miniature version also.

Katie: It would be as tall as the, um, ceiling (gesturing with one arm raised high). Oh, and Marty will just crawl through here kind of, I guess (flipping open a little opening in the side of the dog pen that she later refers to as a “doggie door”).

When the majority of students raise their hands to question the girls’ description of their portable dog pen, Katie and Maria call on their classmates.

Cooper: How would Marty pick it up if it was, like, up to the ceiling and like five feet wide?

Katie: This part is under the ground,

Maria: It's under the ground. There's like a little flap that he can just pull it, and it comes up.

Katie: And it's really, really light.

Maria: Yeah, super light.

Katie: And I'm thinking we should add wheels, so it goes like, woooo (pulling their dog pen model in a circular motion on the floor).

Maria: Yeah, we're going to make, like, little wheels,

Katie: Also, like, we're going to make, like, I think that,

Maria: We're going to make like a little rope here, and he can pull it.

Katie: And like, this is a little button, to make it go, so –

Maria: Yeah, we're going to make buttons or something.

When her attention is on the dog pen construction as an object itself, Katie describes it as being "portable," and lifts it off the ground. Ms. C., in an effort to help the girls clarify, asks if they mean portable for them or portable for Marty, to which Maria confirms that Marty will be able to "pick it up" as well. Katie then fluidly reverts back to describing it as a representation of a dog pen that exists in the story setting, suggesting that Marty will crawl through the "doggie door" to access Shiloh. The other students, noticing the inconsistency, question the conflicting dimensions: Cooper asks how Marty could pick up the dog pen if it was "up to the ceiling and like five feet wide." Instead of addressing his concern regarding incongruity, Katie and Maria respond by generating a number of possible features that make the dog pen even more portable for Marty (i.e., make it super light, add flaps, wheels, buttons). In the moment, they make local adjustments to their design in response to questions asked, prioritizing the need to have an answer for their classmates over the actual feasibility of their ideas.

The girls manage their own perceptions of the dog pen, shifting between and blending their immediate classroom context, in which the physical artifact is the object to which they are referring, and their imagined setting, in which their artifact is a representation of a dog pen that exists in their version of the story. Our interpretation of this exchange is that for the girls, the physical salience of their constructed artifact (the cardboard dog pen) has become a powerful meaning activator itself, which in turn spurs an ontological shift in their discourse (Sfard, 2000). That is, Katie's and Maria's attention and design objective shift from being a representation of a life-size dog pen that would exist in an imaginary space, to the artifact itself, to a toy-size dog pen that children like them or the story character could pull around. Their attention to the dog pen as an object itself is also ephemeral; seconds later, when prompted by another student, the girls describe how Marty will gain access to the inside of the dog pen (a "doggie door"). In their shifting, the girls perceive a confluence of ontologically different entities coexisting in their artifact: one is representational of an imagined setting with a make believe dog pen that is inhabited by the fictional characters; the other is the cardboard object they hold in front of them. The girls do not perceive these two entities to be mutually exclusive: at times, they incorporate relevant aspects of the story into the cardboard version, suggesting and showing how Marty will be able to lift and pull the miniature sized dog pen.

Their perceptions of their dog pen fluctuate depending on the questions and their attention; in the flow of discourse, the girls fluidly shift between and combine aspects of imagined and real contexts. While we would expect Katie and Maria to be caught off-guard by the other students' questions regarding scale, the girls don't skip a beat; instead they both are excited to elicit and respond to their classmates' questions and selectively choose which aspects of the questions to answer, without recognizing a need to reconcile conflicting dimensions. Further, they continue to solicit questions even after they have responded to the minimum amount, and at the end of their presentation, the girls appear joyful and proud, both taking several bows. Their similar reaction, we believe, is evidence of their shared local framing stability. Katie and Maria may be drawing from experiences involving show-and-tell, storytelling, or performing; their framing frees them from needing to meet engineering criteria (e.g., feasibility, functionality) or adhere to the constraints of a specific design setting. Instead, they create meanings and link sequences of events to narrate their tinkering, drawing on plot devices, such as *deus ex machina,* which allow them to resolve complications by conjuring seemingly miraculous resolutions (i.e., Marty's ability to carry the dog pen around *and* go inside of it). The unexpected twist in Katie and Maria's design solution – making the dog pen portable for Marty – surprises their audience. From a narrative perspective, this is a central goal; as Roland Barthes (1975) describes, part of the bliss, or *jouissance*, of a narrative experience comes from breaking expectations. It is possible that within their local framing, which emerged in their interactions with their dog pen and their classmates, Katie and Maria achieve their objectives: the girls exploit the flexibility of their artifact to tell a story that leaves their audience perplexed.

Discussion

In this study, we illustrated the contextually sensitive nature of student framing within a socially and materially rich classroom setting. In each case, we traced unique ways in which students' perceptions of and interactions with materials not only influenced their design ideas; they also involved, informed, and were evidence of their sense of the activity in those moments. For the students, the open-ended and ill-structured nature of the engineering design task supported their pursuits of different end goals. Based on our analysis, we argue that the materials and artifacts played a central role in the dynamics of students' framings, acting as both epistemic pivots and stabilizers by cueing students to draw from experiences they believed to be similar in forming expectations for the task at hand. Students' transient framings were at times generative for learning engineering design; within varying dynamics, they enacted epistemic activities that reflected those of practicing engineers, such as analyzing, perspective-taking, and evaluating, to meet circumstantial aims and objectives. At other times, however, students' framings were less productive for engineering, allowing them to imagine beyond the constraints of the local situation such that they did not need to consider engineering criteria, such as feasibility or functionality.

Materials and artifacts as epistemic pivots and stabilizers. Jack, Cooper, and Thomas' framing shifted and evolved over the course of their designing as they interacted with the materials, their artifact, and with others in the classroom, prompting them to enact complex ways of thinking. For instance, their perception of their artifact, a partially constructed dog pen model with a half-covered roof and "eye hole" tipped them into thinking beyond Shiloh's needs in the fictional setting, to consider the classroom evaluation criteria – what their teacher, classmates, and researchers might need to understand their design. In this subtle shift, they transitioned in their epistemic activity from constructing a small-scale dog pen to coordinating multiple perspectives, negotiating trade offs, and identifying an optimal solution for the situation. For Jack, Cooper, and Thomas, this pivot was productive: it heightened their awareness of multiple contexts and required them to coordinate relevant social-material relations (Suchman, 2000) to meet the needs of both their assumed user (Shiloh) and immediate clients/stakeholders (teacher, researchers, classmates). The boys' subsequent interactions with materials, such as finding and procuring plastic for the dog pen roof, allowed them to become stable in this framing, such that they were able to meet functional and representational aspects of the design task.

As Katie and Maria interacted with materials, their artifact, and others in the classroom, they continually adapted their framing, often aligning their objectives for the task with their perceptions of the materials and artifacts at hand. In our account of their work, we evidenced two pivotal interactions: first, when the girls were gathering available materials, and second, when they were presenting their work. The girls' initial perceptions of and interactions with materials and objects, such as Katie's cardboard tube, spurred a shift in their local objectives for the task; instead of bounding the design situation to the story setting (i.e., West Virginia in the 1970s), the girls expanded their design space to include imaginary entities that would warrant their use of interesting objects. The data suggest that their ideas for referent entities stemmed from the physical characteristics of the objects themselves: a see-through tube became a video camera, pipe cleaners became laser beams, and a LEGO figure became a bodyguard. Their interactions with these materials and reasoning about what they "could be," or represent, in their design are evidence of materials also acting as stabilizers, allowing the students to continue imagining fantastical solutions without needing to adhere to design constraints.

When Katie and Maria presented their design to the class, the girls again pivoted as they were describing and interacting with their artifact. In describing the small size of their model, they suggested that Marty can pick it up too, and Katie picked up the dog pen to show her class; moments later, they reverted back to describing how Shiloh and Marty fit inside the pen (in the story setting). In doing so, they conflated the design contexts, rather than coordinating and managing them. The girls, in this moment, did not see a need to differentiate or reconcile the conflicting scales or settings. Within their shared framing, they freely concatenated design ideas and components, without considering viability or reflecting on one or the other design situation. The open-ended nature of the design task granted Katie and Maria the freedom to exploit the flexibility of representations, both materials and their artifact, in their own way; rather than conforming to the disciplined perception of the class, they remained perceptively agile, seeing objects in multiple ways.

Pretending in engineering. As students' framings were mediated by their interactions with materials and artifacts, they created representations that aligned with their sense of the task. On the surface, there are elements of the students' work that appear similar; in particular, both groups in this study incorporated "pretend" features into their designs. However, the subtle differences in students' pretending evidence unique aspects of their local framing, which have implications for engineering design learning. For Cooper, the pretend roof manifested in his coordination of the classroom and fictional design criteria; he prioritized the immediate clients' need to view the inside, and to communicate the idea, he used “pretend” to overcome the limitation of classroom materials. Pretend, in this instance, did not drastically alter his group’s design or their uses of materials as representations; instead, pretend served as a scaffold to convey their design idea (i.e., a “see through” roof) with limited materials. His suggestion for a pretend roof, we believe, resembles the types of assumptions engineers make in practice, especially when developing prototypes under time and resource constraints.

This stands in contrast to Katie and Maria’s pretending, which *became* a central objective in their design activity. Their interactions with raw materials, elements that did not already hold representational meaning for them, provided them with flexibility in generating referent entities for the materials; in exploiting the representational flexibility, Katie and Maria pretended what the materials could be. For them, pretend was an integral part of their framing, allowing them to think creatively without being held accountable to either the classroom or story constraints.

Conclusions and Implications

A glimpse into these cases suggests that students have a wide range of abilities for engineering design and how they enact those abilities has to do with what they think the task is about. As we showed in this study, when given the same open-ended design task in an elementary classroom, students may form very different purposes for the task; their framings are continually mediated by their social and material interactions. These dynamics are often nuanced and subtle, often involving productive engagement in engineering design (e.g., conceptualizing imaginative solutions, accounting for multiple perspectives), but may also lead to less productive engineering assumptions and reasoning (e.g., imagining purely fantastical solutions). Importantly, their reasoning and actions in these moments, sometimes involving pretending or storytelling, should not be generalized as being random, incoherent, or simplified to “mere playing” or “trial and error” (Roth, 1996); instead, they should be taken as means to achieving different ends. In pursuing solutions, students develop their own sense of logic and purpose, engaging in epistemic activities that make sense and allow them to “bring forth aspects of the story they wish to tell” (Nemirovsky & Tierney, 2001, p. 98).

While we believe that students’ agency, imagination, and playfulness are of critical importance in engineering design, we also recognize that the freedom of open-ended design situations raises challenges for researchers and educators in elementary settings. A central challenge that emerged in this study involves managing open-endedness in design, especially when students are using familiar materials representationally. Students’ understandings of “what counts” as engineering may be obscured by their understandings of “what counts” as a representation; that is, students may create imaginative dioramas without needing to consider feasibility or functionality of design solutions because making imaginative representations is a familiar activity for them. On the other hand, tightly constraining and defining design tasks may prevent students from experiencing the “messy,” complex nature of engineering design; further, well-defined design tasks may shift students into playing the “classroom game”

(Lemke, 1990), in which they focus on how they are evaluated as students rather than acting as evaluators of their own designs (see Chapter 4). Thus, the main challenge for educators is to anticipate different dynamics in student engagement and to bound open-endedness responsively, such that students have opportunities to navigate design situations, but recognize the need to adhere to design contexts and constraints.

This study, in addition to our data from other studies (e.g., Watkins, Spencer, & Hammer, 2014), indicate that students have abilities to navigate and manage open-endedness in engineering design; however, some may need more support and structure in navigating design situations, particularly with respect to understanding the role of engineering representations, identifying criteria and constraints, and making assumptions. For example, to reduce the possibility of students using materials in purely imaginative, representational ways (thereby neglecting the design situation and constraints), teachers may scaffold the uses of materials and representations in a variety of ways. One possibility is to provide a list of materials before students begin sketching or have the students collectively generate a list of materials that make sense for a design context. Another possibility is to hold students responsible for specifying and labeling their design sketches with the materials they intend to use for their prototypes or representations. To scaffold students' abilities to evaluate their designs, teachers may have them articulate or discuss with each other how they plan to test, how they will know if "it works," and/or how they think it will help a particular client overcome a problem. Scaffolding engineering activities in these ways may help students form tacit understandings of representations in engineering design, and lessen the likelihood of generating imaginative solutions that do not have functionality or feasibility requirements. With subsequent activities, students' framings for engineering may become more stable, such that meeting specified design criteria and constraints are implicit in acts of designing.

In this study, we illustrated the complex, nuanced dynamics of student sense-making within a materially-rich classroom setting, and shed light on students' productive beginnings in engineering design. Our findings, we believe, only skim the surface of a vastly uncharted field of elementary engineering education, and warrant deeper research into the dynamics of student engagement. Further research will not only provide insight to students' nascent abilities for engineering, it will also inform the development of instructional practices and curricula, and empower educators to identify and respond to students' engineering reasoning during classroom activities.

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Chapter 6: Dynamic engagements in engineering design

Novel Engineering is an instructional approach that involves the integration of engineering and literacy. In previous studies, we have found that elementary students take up Novel Engineering activities in varying and dynamic ways; at times, students may foreground the needs of story characters, and at others, they may prioritize their teacher's expectations or the technical aspects of the design in others. We have found that students' tacit understandings of what is taking place in the activity, or their *framing*s (Goffman, 1974), interact with their engagement in engineering reasoning and acting (McCormick & Hammer, *under review*, Chapter 4; McCormick, *under review*, Chapter 5).

This study builds on and is motivated by previous work. Here, we examine the nuanced dynamics of student framing to understand how students coordinate and adapt framings within moments. By conducting a fine-grained analysis of student discourse, we show that students' *in the moment* framings involve their coordinating of multiple kinds of activities, such as solving problems for their fictional clients, doing a classroom project, and making a functional project. We argue that students' coordinating framings are evidence of their nascent abilities to navigate engineering design processes. We discuss implications for research and practice, particularly the importance of cultivating students' abilities to coordinate multiple kinds of activities in engineering design.

Dynamic engagements in engineering design

Introduction

In engineering design, knowing how to “make sense of uncertain design situations” (Schön, 1983, p. 40) is at the heart of the discipline; engineers in practice collectively bring structure to design situations by organizing, negotiating, and coordinating multiple aspects of the task (Bucciarelli, 1988; Schön, 1983; Stevens, Johri, O’Connor, 2014; Suchman, 1987). In classroom settings, however, students are more often given well-defined engineering tasks (Jonassen, 2014) and are tested on specific content knowledge or design processes (e.g., Massachusetts State Frameworks, 2012). We argue that students’ abilities to navigate “messy” design situations, i.e., those that are open-ended and ill-structured (Jonassen, Strobel, & Lee, 2006), are central to their development in engineering design. In this study, we show how a group of third grade students coordinate multiple kinds of epistemic activities in their pursuit of an optimal design solution.

This study builds on and is motivated by previous research in which we examined the dynamics of student engagement in Novel Engineering activities. In Novel Engineering activities, students identify problems that occur in children’s literature and engineer solutions to help story characters. The activity is inherently open-ended and ill-structured: students scope problems that occur in stories and use classroom materials to engineer solutions. In prior research, we have shown wide variations in how students make sense of Novel Engineering activities: at times, they attend to the story characters as their fictional clients, while at other times, they prioritize the expectations of their immediate classroom, or focus on the functional parts of the design. We argued for understanding these differences as variations in their sense of "what it is that's taking place," or their "framing" (Goffman, 1974, p. 8) of the activity. As we describe below, our previous findings indicate that students' framings influence their participation in engineering reasoning and acting.

Our initial study involved a close examination of two students who, the data suggested, were stable in framing the activity as designing for characters in the story. For the pair of fourth graders, developing an optimal solution for their fictional client was a central objective; their actions of inferring design criteria and constraints, making informed assumptions and estimates, co-constructing scaled representations, and defining evaluation criteria served a purpose in helping them achieve this objective. We argued that their persistent attention to the story situation was evidence of their stability in framing the task as beginning engineers: the students continually reflected on and responded to their clients' needs, even when they were in competition with a teacher-defined test (McCormick & Hammer, *under review,* Chapter 4).

In a related study, we showed that students dynamically shift in their framing of the activity as they interact with others in the classroom, materials, and artifacts. In some cases, students' interactions with materials spurred deviation from engineering design, allowing them to imagine fantastical solutions without considering feasibility and functionality; in others, their interactions supported complex reasoning for optimal solutions (McCormick, *under review,* Chapter 5).

An instance of the latter occurred as students were considering pros and cons for different design alternatives based on the available materials. As they compared alternatives, the students balanced trade-offs, aiming to provide comfort and safety to their fictional client while maintaining the ability to communicate their design idea effectively. We argued that the students, in this moment, were not simply shifting between thinking about the story and their immediate classroom; they were negotiating how to meet the needs of both their fictional client (user) and immediate stakeholders (teacher, researchers, classmates). That is, their multifaceted framing of the task involved their attention to multiple kinds of criteria (i.e., those of story and classroom). To meet these criteria, the students engaged in engineering activities, such as considering alternatives, reasoning about trade-offs, and defining an optimal solution. The complexity of student framing in this interaction motivated our current work.

Our purpose in this study is to examine framing dynamics more closely, specifically how students coordinate multiple framings *within* a moment, to understand how these dynamics involve engineering reasoning and acting. As we describe below, students' abilities to make sense of "messy" engineering design situations is not a place of focus in elementary engineering education; more often, researchers measure students' abilities to recall discrete design process steps in a specific order. Here we take a different approach by examining how students organize their own epistemic aims and activities as they pursue design solutions. We do so by examining students' tacit sense of what the activity is about in each conversational turn. We develop a coding scheme to capture the nuanced dynamics of student framing throughout their design experience and conduct in-depth discourse analysis on select excerpts.

In our analysis, we show how the third grade students' framings involve their combining strategies of action to meet clients' needs, the expectations of their teacher and classmates, and the technical aspects of their design. We argue that the students' coordinating framings, which involve organizing epistemic activities, are evidence of their nascent abilities to navigate engineering design processes. We then discuss the importance of cultivating students' abilities to coordinate multiple framings in engineering design.

Assessing elementary students in engineering design

In elementary engineering education, researchers often focus on students' knowledge of specific design process steps and the way those steps are connected in a sequence (e.g., Dyehouse, Diefes-Dux, & Capobianco, 2011; Hsu, Cardella, & Purzer, 2012; Tafur, Douglas, & Deifes-Dux, 2014). In most cases, researchers use assessment tools, such as multiple-choice questions and interview-based protocols based on five or eight step design process models (Cunningham & Lachapelle, 2007; Cardella, Hsu, & Ricco, 2014; Gaskins, Kukreti, Maltbie, & Steimle, 2015). For instance, researchers have focused on whether students are able to identify canonically correct design process steps (e.g., Cunningham et al., 2007), while others have measured whether students use correct terms, list the terms in the correct order, and are able to recreate a representation a the design process cycle (Gaskins et al., 2015).

The findings from these studies indicate that students may not know the steps of the engineering design process or how those steps are ordered. For instance, Cardella and colleagues' (2014) findings indicated that most students missed the "Ask" category and went straight to "Plan" as they started designing. Similarly, Gaskins et al. (2015) found that many of the students know the correct terms in the engineering design process, but are unable to recreate representations of the design process cycle.

These design process-focused assessments facilitate collection of large data sets and comparisons of student knowledge across time and geographic locations (Duncan & Hmelo-Silver, 2009; Litzinger, Lattuca, Hadgraft, & Newstetter, 2011; Crismond & Adams, 2012). However, the larger data sets come at the cost of understanding and supporting students' abilities to engage disciplinary engineering design. Numerous engineering practitioners have expressed concern that the emphasis on discrete, sequential step-by-step design process does not reflect the complexity of the discipline, nor does it prepare students for real world problems (Bucciarelli, 1994; Brophy, Klein, Portsmore, & Rogers, 2008; Johri & Olds, 2011). Schön (1983) describes why learning engineering as a discretized set of steps is problematic:

> Designing is a holistic skill (which) one must grasp as a whole in order to grasp it at all. Therefore, one cannot learn it in a molecular way, by learning first to carry out smaller units of activity and then to string those units together in a whole design process; for the pieces tend to interact

> with one another and to derive their meanings from the process in which they are embedded (p. 159).

Our aim in this work is to understand how students manage the interacting "pieces" as they co-construct meanings of the design activity; in other words, we aim to understand how students organize epistemic activities as they are engaging in the design activity.

To understand students' productive engagement in disciplinary engineering design, we draw from ethnographic accounts to understand how engineers in practice navigate design processes. These accounts indicate that engineers continually analyze and evaluate designs in light of many dimensions, including material, social, and economic, and stakeholder criteria (Bucciarelli, 1994/2002; Stevens & Hall, 1998; Suchman, 1987; Trevelyan, 2010). Rather than progressing through a set of discrete steps, engineers fluidly combine strategies of action throughout the process as they interact and negotiate with involved others, the design situation, and solution possibilities (Goel & Pirolli, 1992; Schön, 1983; Stevens, 2000).

In the following, we describe *framing* as an analytical tool to understand the dynamic ways students make sense of a Novel Engineering activity. By attending to student framing with a fine-grained unit of analysis, we show that students, in any given moment, are coordinating multiple, interacting framings and that they organize epistemic activities accordingly.

Theory and Conceptualization

The central idea of framing is that individuals generalize knowledge from past experiences as cognitive structures of expectations, or “schemas” of activity (Bartlett, 1932). As individuals experience new situations, they draw from and adapt schemas from previous activities to make sense of the present moment. In this view, framing is an individual’s dynamic, ongoing, and often tacit process of making sense of the experience.

Notions of framing are rooted in anthropology (Bateson, 1972), sociology (Goffman, 1974), artificial intelligence (Minsky, 1975), and linguistics (Tannen, 1993). Researchers in these areas have found that within a given community, there are types of activities that become familiar, from games to lessons to rituals and common experiences. People in a community construct similar schemas for activities, which become “basic frameworks of understanding available in our society” (Goffman, 1974, p. 10). A classic example of a culturally shared schema is that of dining at a restaurant (Schank & Abelson, 1977). From their own experiences, diners form similar structures of expectations for what happens in a restaurant, including the kinds of interactions, smells, behaviors, and so on. In framing a restaurant experience, the individual adapts schemas of expectation to reflect the present moment; a new menu or different waiter may lead to subtle adaptations in schema.

Similar to culturally shared schemas for dining in restaurants, students share a wide range of schemas for school-related activities, e.g., recess, spelling tests, doing science. For instance, students may frame a classroom-based science activity as memorizing and producing answers for a test in one moment, and as an opportunity to reasoning about phenomena in another (e.g., Hammer et al., 2005; Hutchinson & Hammer, 2010; Berland & Hammer, 2012). We conjecture that students also share schemas that reflect their experiences with stories, being students in the classroom, and making things that work, and that they combine and adapt these schemas in the moment to make sense of what is taking place in engineering design. We show evidence of these dynamics in our previous work (McCormick & Hammer, *under review*, Chapter 4). Others have shown similar patterns in student engagement in design activities (Roth, 1995; Jurow, 2005); Jurow (2005) illustrates how students shift among and combine their ways of participating to include the classroom expectations, disciplinary mathematics, and the fictional design situation.

Methods

This study is part of a larger research project entitled Novel Engineering that is funded by the National Science Foundation (DRK-12 grant 1020243). We are currently working with fifteen elementary teachers (Grades 3 – 5) in nine schools of varying demographics. Our work with teachers involves facilitating professional development experiences over the summer and during the school year, co-developing classroom lessons and activities, and supporting teachers in classrooms during implementation.

Research context. The focal group in this study consists of four third grade students (one girl, three boys) in a rural New England school. The students had participated in two prior Novel Engineering design experiences earlier in the school year. For this project, the students were engineering solutions to problems based on the book *From the Mixed Up Files of Mrs. Basil E. Frankweiler*, by E.L. Konigsberg. In the story, a brother and sister pair (Jamie and Claudia) run away from home and hide out in the Metropolitan Museum of Art in New York City (museum). While they are there, they encounter various problems (e.g., running out of food and money and the inability to find a place to sleep at night), and eventually have to solve a mystery. In the classroom, the students are engineering solutions to help the story characters hide out in the museum. The project extended over consecutive three days, for approximately 45 – 60 minutes per day.

Analytic tools. We collect *in situ* video data during all engineering activities to account for multiple dimensions of the learning environment and the flow of activity. As previous researchers have noted, videos provide a medium for analyzing naturally occurring phenomena (Derry et al., 2010; Jordan & Henderson, 1995). During classroom activities, our research team focuses small, tripod-based cameras on randomly selected student groups, often with additional microphone units to more adequately capture sound. Our data sources include direct observations, videotapes of design-related activity, field notes, and students' engineering artifacts. Our selection of data for this study is based on the availability of video data on the group; we collected video data of their work for all three days.

In analyzing the video data, we draw from interactional analyses of observational data (Jordan & Henderson, 1995) and discourse analysis (Gee, 1994; Schiffrin, 1994; Tannen, 1993), which are based on the notion that knowledge and action are situated in social and material ecologies. The nuanced linguistic features of framing provide insight into what individuals mean by what they say and how they say it (Tannen, 1986). We see evidence of framing in the substance of students' speech and in linguistic markers associated with speech acts, such as register and tone[12], as well as nonverbal actions, such as gestures, body positioning, and interactions with materials (Ribeiro, 2006; Tannen, 1993; Tannen & Wallat, 1993).

We also draw from research on participation frameworks (Goodwin, 1990; O'Connor & Michaels, 1996), which examine how individuals coordinate framings and the discourse that constitute shared, or coherent, framings. We use *positioning* to refer to how individuals orient themselves and their talk according to what is most salient in their schema at a given moment, where meaning can be disputed, refuted, or negotiated (van Langenhove & Harre, 1999; Ribeiro, 2006). More specifically, we document how students position their ideas, or assume "footings" (Goffman, 1981, p. 128), with respect to different aspects of the activity, such as the story setting or classroom expectations.

Identifying and establishing codes. Our research team identified patterns in student engagement over four years of collecting and analyzing data from the Novel Engineering project. In particular, we noticed that students, at times, become focused on attending to the story and characters' needs, and at other times, they prioritize the immediate classroom context, including the expectations, norms, and rituals. These patterns form the basis for our coding scheme. In the

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[12] Patterns in vocal register include *silly* (when students are laughing or joking), *announcing* (when they are communicating to peers or teacher during sharing), and *pretending* (when students take on other roles).

former, students are framing the activity as involving the *story*; evidence of *story* framing include includes students taking perspectives of the characters, designing for situations in the story, and adhering to the story setting. In the latter, students are framing the activity as a familiar *classroom* based project; evidence of *classroom* framing includes students attending to norms or rituals or the classroom activity, or acting cognizant of how they will be evaluated.

We developed the initial coding scheme as a tandem structure, in which *story* and *classroom* were both always present in students' framings, but to greater or lesser degrees. Our aim was to capture variations in students' foregrounding and backgrounding of *story* and *classroom* framings. This initial scheme proved to be fraught with ambiguity, especially in moments when students building and testing their designs. For example, when students were constructing physical artifacts to represent the story using classroom materials, some researchers argued that they were foregrounding both the story and classroom, whereas some argued for only one or the other. In the data, we could not isolate explicit evidence of both *classroom* and *story* framings for these occurrences.

Our collective analyses of the video data led to many discussions around what should count as evidence of *story* and *classroom* framings. Through these discussions, another coding category emerged: *making*, which marked evidence of students attending to the technical aspects of the design, such as materials and functionality. By disaggregating *making* from *story* and *classroom* framings, we were able to identify moments when students were discussing, reasoning, or wondering about how their design would function, specifically with respect to story and classroom framings.

In coding the data, we did not account for different levels or relationships among framings; we simply coded each conversational turn for evidence of *story*, *classroom*, and/or *making* frames. To be sure, a single utterance could have evidence of all three framings if the student is thinking about how to make a design functional while meeting classroom requirements.

We describe each coding category below and provide more detailed descriptions in Table 1.

Story: We code for *story* when students are foregrounding aspects of the story, such as attending to characters' needs, inferring constraints of the story setting, evaluating by imagining, or simulating how solutions would work in the story.

Classroom: We code for *classroom* when students are foregrounding aspects of the classroom, including adherence to classroom expectations, such as concern for how they will be evaluated (e.g., use of correct vocabulary or including specific information for the project), established rituals (e.g., presentation of work or question and answer time), or accountability for fulfilling assigned roles in group (e.g., acting as "scribe").

Making: We code for *making* when students are foregrounding the technical aspects of the design, such as when they are discussing the materials they need, the physical construction of the design, or when they are building and testing their constructions.

Coding process. Before coding, we collected and transcribed all available video data from the group[13] over three days, and concatenated transcripts to form one longer transcript, consisting of approximately 93 minutes (1100 conversational turns). We applied codes to each individual student's conversational turn. As described above, each turn could be coded as any combination of *story*, *classroom*, and/or *making*; for example, one conversational turn may have evidence of only *story* framing or of all three. We did not code for times when the students were off-task (e.g., talk about using restrooms or losing pencils).

We measured inter-rater reliability as a way to calibrate our assumptions regarding what counts as evidence of particular framings. To measure inter-rater reliability, the second coder was given all video data, a complete transcript with no codes applied, and Table 1. She selected and analyzed random chunks of data from each day of the students' activity (approximately 20% of the data). We calculated Cohen's kappa to be 0.94. We attribute the 6% disagreement to data that were ambiguous with respect to framing; we describe these data and our reasoning in Appendix A.

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[13] We did not include data during which the teacher was leading a discussion or other groups were presenting.

Table 6-1: Coding categories of student framing

Description of coding categories	*Examples*	
Story		
Related to story	"I've got an idea to hide in the Eygyptian Wing."	🟥
Attention to characters	"It'd be a big sacrifice though, cause they're using up Jamie's money." (Referring to characters as "Jamie and Claudia," "They," "he" or "she")	
Attention to story setting	"Oh, and the American Wing Cafe is close to the Egyptian Wing."	
Pretending/simulating how it will work in the story	Using bodies to show how characters would use it	
Working on design that is true to story	Considering how it "would" work	
Classroom		
Roles in group	"Scribe, write it down. I'm not the scribe."	🟦
Meeting classroom requirments	"Wait, we need three solutions at least."	
Staying on task/topic	Get back to- Ok, back on task.	
	"Well, we changed our topic since the last time."	
Attending to classroom norms and rituals	"So, should someone shop for ideas?"	
Explicitly deciding "what counts" as part of classroom engineering project	"Um, isn't looking for places to hide not generally engineering, it's just-"	
Presenting or Demosntrating in class	"Should we demonstrate with it? Ben? I'm going to demonstrate. Wait, is everyone who wants to see here?"	
Discussing how to present and representing	"Or we could just do both (ideas) for the presentation."	
Functional		
Considering materials and specific components of physical design	"Guys, we got a hook. Ok, where's the string?" "No, it's too thin/thick. Look, it -" "Yes, I know.We can add this to this to improve it."	🟩
Constructing	"Guys, I can. Guys, I can stand on the chair since I'm the tallest, I can hold it up and someone can cut the string."	
Analyzing and improving physical design	"Now we need another thing to weigh it down. To make it go up."	

Coding data. The significance of coding is that it allowed us to track evidence of student attention to *story*, *classroom*, and *making* schemas of activity within students' interactions and across time. For example, a sequence of multiple *making* codes extending over several minutes or conversational turns might suggest students were stable in framing the activity as making something functional, while a sequence involving sporadic presence of *story* and *classroom* might suggest that students were negotiating what the task was about, toggling between expectations related to doing something for the story and for the classroom.

For a deeper investigation of framing interactions, we conducted discourse analysis on three excerpts, focusing specifically on how students position themselves and their ideas with respect to the story, the classroom, and making. We selected excerpts for deeper in-depth analysis based on student progress in their designing (early, midway, and final) and on the varying framing dynamics that emerged in the coding. We labeled the excerpts according to our generalizations of the students' activity, i.e., scoping the problem, constructing prototypes and discussing different ideas, and testing and presenting their solution to the class.

Data and Analysis

In this classroom, the teacher, Ms. M., had read over half of *From the Mixed Up Files of Mrs. Basil E. Frankweiler* aloud to the class before stopping to do an engineering activity. As Ms. M. read the story in the weeks prior, she had her students reflect on the problems the main characters were facing and collectively list the problems on a large piece of chart paper in the front of the classroom. She then had students write down the engineering problems they wanted to solve for the characters, and grouped students based on their matching problem choices.

Ms. M scheduled the main engineering component of the Novel Engineering project over three days. On the first day, the students discussed problems and brainstorm solutions; on the second day, students constructed, tested, and revised solutions as needed; on the third day, they finished their design solutions and presented to the class.

The four students in this study, Colin, Allie, Ben, and Chico, decided to help the characters safely make it past the guard at night by engineering a distraction mechanism.

Overarching Design Trajectory

Figure 6-1 shows our coding of the group's collective framing over the course of their Novel Engineering design experience. The coding reveals different dynamics occurring on each of the three days, which we associate with early, midway, and final design phases. We first describe, in general, what the coding reveals with respect to the presence of codes on each day. We then examine the framing dynamics on a finer grain size by conducting discourse analysis on three excerpts.

On Day 1 (0 to 23 minutes), students' framings of the activity involve consistent attention to the story, as indicated by the presence of *story* codes, with increasing attention to classroom expectations, as indicated by the increase in presence of *classroom* codes (16 to 23 minutes). On Day 2 (23 – 1:17 minutes), students' framings of the activity involve consistent attention to making things, as indicated by the presence of *making* codes, in combination with their attention to *classroom* (38 – 45 minutes) and *story* (38- 50 minutes) expectations. On Day 3 (1:17 – 1:27 minutes), students' framings of the activity involve attention to classroom, story, and making expectations for the majority of the time, as indicated by the presence of *story, classroom,* and *making* codes.[14]

Figure 6-1: Evidence of student framing during design activity

Scoping the Problem (Day 1)

The following excerpt occurred during the initial planning stages. As described above, our coding of the data revealed consistent presence of *story* framing during this time. In this excerpt, the four students are sitting in a circle, some with pencils and paper, and taking turns looking at a map they had printed out of the Metropolitan Museum of Art. Here, they are brainstorming possible places for Jamie and Claudia (the story characters) to hide.

Excerpt 1: Students' problem scoping discussion.

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[14] The ten minutes of video data on the third day is primarily during their presentation.

line	time		Story	Class	Make
97	6:32	Colin: I've got an idea on where they– there's one near the Egyptian Wing.	🟥		
98		Colin: They could hide in the tomb, or hide in a coffin, dressed as a mummy and scare tourists potentially. (*laughing, makes mummy gesture)*	🟥		
99		Allie: Where are the bathrooms?	🟥		
100	6:46	Ben: We can act that out. I can be a mummy. (*rising intonation*)	🟥		
101		Chico: I found the [bathrooms!	🟥		
102		Ben: [Guys,	🟥		
103		Colin: I know; there are multiple ones.	🟥		
104		Chico Hey, it's BOYS NEXT TO GIRLS!	🟥		
105		Ben: Ok, I have an idea!	🟥		
106		Chico: Coff…[in.	🟥		
107	7:03	Allie: [Guys, I have a plan already. See? [Wing. Egyptian Wing.	🟥	🟦	
108		Colin: [Hide in a - HEY, there's a restroom near the [Egypt Wing!	🟥		
109		Chico: [Hide in cof:::fin.	🟥		
110		Colin: So, where should they hide? In the Egypt?	🟥		
111		Chico: Hide in *Sar:KOHF::ahh::gus*. It's called a *Sarcophagus*.	🟥	🟦	
112	7:20	Colin: I don't CARE what it's called!	🟥		
113		Ben: Who CARES?	🟥		
114	7:24	Colin: Ok, so I've question.	🟥		

The students, in this excerpt, are tacitly negotiating what this activity is about as they brainstorm solution ideas. By positioning their ideas and each other's ideas with respect to design criteria, they begin to hold each other accountable to what they to be viable options.

In the first line, Colin foregrounds the story: he announces he has an idea for where "they," referring to the story characters, can hide, and without pausing, describes that they can hide near the Egyptian Wing, in a tomb or in a coffin, and "scare tourists potentially." As he describes the potentiality of scaring tourists, Colin's register changes from being serious and task-oriented to being silly and playful: he acts out his idea by lying on the floor with his hands by his side and popping up (to show how they would scare people). This subtle shift in footing allows him to manage the reception of his proposed idea (hiding in the Egypt Wing) by ensconcing it in a silly gesture, possibly creating a safe space for ideating.

Allie, Ben, and Chico react in different ways, each of which brings new meaning to the group's shared sense of "what it is that's going on" with respect to the design activity (Goffman, 1974). Allie looks to the map of the museum and asks where the bathrooms are; her question orients them back to the story, specifically in thinking about where Jamie and Claudia hide in the story (the museum bathroom). Ben, latching onto Colin's joking register, adds that they can "act that out" and he can "be the mummy." He interacts with Colin's idea, implicitly layering a criterion of a design solution that they can physically represent their design solution so that others can evaluate it. Chico, looking at the map, responds to Allie, calling out that he found the bathrooms. Chico's response tips them into a slightly more narrowed pursuit, anchoring what they are doing in the actual design context of the museum (*story*). Colin then reacts to Chico, asserting that he knew that information – that "there are multiple ones"; his shift back to a more serious, task-oriented register allows Colin to align his framing with Chico and to establish his proximity to the design situation.

In the sequence of turns that unfold, the students continue to position themselves socially and epistemologically: they mark their own production of ideas and position those ideas with respect to each other, the story, the classroom, and the functional aspects of the design. Allie and Chico both draw from classroom framings during the brainstorming process. Allie, who was earlier assigned the role of "scribe," establishes her position as documenting the group's work: in line 107, she holds up the notecard the teacher gave to them to list their ideas, and reminds the others that she has "an idea already," (i.e., Colin's "Egypt

Wing” suggestion). In this, she aligns her expectations for their assigned task (i.e., filling out the notecard), and positions herself to meet those expectations by documenting solutions for the story (*story* and *classroom*). Similarly, as Chico contributes details from the map, he makes a point to correct the other students’ terminology; in this, he adheres to classroom expectations of using and establishing correct vocabulary words from the book (*story* and *classroom)*.

Colin and Ben, however, persist in orienting to and designing for the story. Colin considers advantages of hiding in the Egypt Wing (e.g., access to materials to use for hiding; proximity to bathrooms). When Chico corrects Colin’s vocabulary (“It’s called a sarcophagus”), Colin disregards Chico’s correction (“I don’t care what it’s called”). In this, Colin makes explicit his foregrounding of the *story*; his main purpose in this moment is to identify an optimal place for Jamie and Claudia to hide, not to focus on using the right words. Ben follows suit, aligning himself with Colin’s foregrounding (“We don’t care”).

This brief exchange evidences transient fluctuations and tensions among the group members as they brainstorm and consider each other’s design ideas. The differences in their individual framings allow them to begin bounding the space of possible solutions; by drawing on their own expectations for what the activity is about, the students bring to the fore their own assumptions, design criteria, and constraints. In doing so, they collectively begin to converge on what counts as a viable solution: it has to make sense in the story setting, be demonstrable in the classroom setting, and meet the requirements of this particular classroom task (e.g., listing ideas on a worksheet or using correct words).

At this time, however, the students had not addressed an implicit objective of the engineering design task – i.e., designing a *functional* solution for the characters. In their overarching *story* framing, designing a place to hide would solve the characters' problem. The need for functionality arose twice on the first day in the students' interactions with Ms. M. and their classmates: Ms. M. suggested that they "design something to help (the characters) hide," and another student remarked, "Looking for places to hide is not generally considered engineering." Both of these interactions imposed explicit criteria associated with other framings of the activity: to meet classroom expectations and to count as *engineering*, their solution would need to be functional in the classroom as well as the story.

In response, the group further refined their initial problem, "hiding," to address a central problem having to do with hiding: Jamie and Claudia's inability to travel through the museum at night without being seen by the night guard. They designed a rope and weight system that Jamie and Claudia could build and use to distract the night guard. As the students conceptualized, Jamie and Claudia would hang a small box with money on a hook from the ceiling, and hold the other end of the hanging string from a specific hiding place. At the right moment, Jamie and Claudia would let go of the string when the night guard was near, the guard would be distracted and pick up the money, and the characters could then run between hiding places.

Constructing prototypes and discussing ideas (Day 2)

The following excerpt occurred on the second day as the students were building prototypes. As described above, our coding of the data on Day 2 evidenced students' overarching consistency in their attention to *making* things, at times coupled with attention to *story* and *classroom* framings of the activity. Here, we explore an excerpt that shows evidence of both *story* and *making* framings (lines 731 to 739), followed by interactions between *story, making,* and *classroom* framings (lines 740 – 747).

In this excerpt, the students are working on a small-scale cardboard model to determine how to optimize the amount of time Jamie and Claudia would have to run past the guard. Ben is on the floor working on a scaled model (a cardboard box that represents the museum wall), while Allie and Chico are making representational figures of Jamie and Claudia. In line 733, Colin proposes a revision of their idea. To communicate his revision to Ben, Colin uses a marker and a nearby piece of cardboard to sketch the improved mechanism. At one point, Mary, the first author and research in the classrooms, asks the students a clarifying question.

Excerpt 2: Students discussing different ideas.

line	time		Story	Class	Make
731	12:35	Colin: I've got an idea on how they– it's rea[:::son– oh, sorry.	🟥		🟩
732		Ben: [Oh NO!	🟥		🟩
733		Colin: Sorry. It's reasonably simple and I think, and it would erase the, the, all the tracks. It would erase the ability of the, the – °well, it'd make it harder for the night clerk to know what they were doing.	🟥		🟩
734		Ben: How.	🟥		🟩
735		Colin: [telling register] Want me to show you *how?*	🟥		🟩
736		Ben: Ok.	🟥		🟩
737	25:58	Colin: So, there would be a hook on top of the string with the coin. And there'd be a latch here, [*pointing to a part of the sketch he has drawn on a piece of cardboard to show the position*], and they could pull the string. Well, they're holding the string there with one hand – Jamie and Claudia – when the penny is up. When they let **GO**, though, the penny would fall, the hook would fall off this hook and then the penny would go to the ground without a trace of, without him being able to trace it back to where Jamie and Claudia are.	🟥		🟩
738		Ben: Hm. [*looking at their model*] But, but wouldn't they have an easier chance of being caught if they were to let go ri:::ght here [*holds string at a point at the corner of their model]*?	🟥		🟩
739		Colin: Hm, [*Looking up*]	🟥		🟩
740	26:30	Ben: I have an idea! [*Holding one finger up in the air*] We can do it– ***both*** ideas. We can do both ideas.		🟦	
741		Colin: Ok?	🟥		🟩
742		Ben: Do you know ***HOW***? See, we have [this box,		🟦	🟩
743		Colin: [Oh, they-	🟥		
744		Ben: And we can do one idea on this side [*pointing to side of box*], and one idea on this side [*pointing to other side of box*].		🟦	
745		Mary: Oh, and think about what works best?			
746	26:58	Colin: Yeah.	🟥		🟩
747		Ben: Or we could just do both for the *presentation*.		🟦	

The students first establish a shared framing in which they are using representations to co-construct a solution for the design setting (lines 731 – 739). Ben then shifts to considering classroom objectives (line 740), which in turn spawns a sequence of competing ideas regarding design priorities. In the following, we describe the local stabilities and fluctuations that occur in their exchange.

In lines 731 – 739, Colin and Ben appear stable in orienting to both the story and the functional aspects of their design: they represent their design idea as it occurs in the story context by using entities in their immediate environment, including their bodies and the materials at hand. Colin is bending down next to

Ben (who is working on the floor) to show him a sketch he has created on a loose piece of cardboard. Colin's way of describing his design idea and the substance of the idea itself provide insight for how he is orienting to the task. He initially describes the idea as being "reasonably simple"; at this point, it is not clear whether he means that it will be simple (and therefore feasible) for the story characters to do in the museum at night, or if he means it will be simple for him and Ben to do for their project with the given materials and time limitations. As he continues to describe his idea ("well, it would make it harder for the night clerk to know what they were doing"), his voice changes to a whisper and he crouches closer to Ben. We suspect that Colin, in this moment, is embodying Jamie by hushing his voice and acting stealthily as he describes how his idea will prevent the characters from being discovered. Colin's framing involves a transient coincidence of schemas[15]: he changes his voice and gestures to animate the characters, specifically their need to stay hidden (*story*), and communicates how his idea for a latch release will function more effectively to prevent the characters from being caught (*making*).

When Ben asks how the design will work, Colin responds "Want me to show you how?" In this question, his voice becomes more assertive, indicating a shift in footing; no longer animating the characters as users of the design, he positions himself as an expert to describe the logistics and features of the design *for* the characters. Although Colin is no longer animating the characters, he

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[15] The ephemeral nature of his blended framing in this moment may also reflect phenomenon that Tannen and Wallat (1993) describe as "leaking frames," occurring when the cognitive load of juggling multiple frames causes intersections or "leaks" into other frames, often leading to slipping of vocal register.

continues to blend *story* and *making* framings as he interacts with their sketch and the physical model of their design. Colin describes specific features of their representations as if they are entities in the design setting (line 737): he specifies (by pointing to places on his sketch) the location of the latch as “here,” the place from which Jamie and Claudia hold the string as “there,” and the hook that will release as “this hook.”

To understand Colin’s design idea, Ben must align his framing, such that they are both using the materials at hand to evaluate the design idea based on how it would work in the story context. As Colin describes his idea, Ben first examines Colin’s sketch; he then looks to the physical model, holding the small box that is hanging from a string, and looks up the ceiling and back down to the floor. We suspect that Ben is translating Colin’s proposed design concept to multiple media: he considers the substance of Colin’s idea, then maps it onto the physical artifact to understand how the mechanism would work in their scaled physical model, and lastly, he considers how it would function as a life-size model in the design setting (looking up to the ceiling as Jamie and Claudia might do and considering the specific location from where they would release the string). By aligning his framing to blend *story* and *making*, Ben is able to use the physical model to interact with the conceptual aspects of Colin’s idea and to explore alternative outcomes, specifically related to the release point (“right here”).

The students’ local stability in this shared framing is ephemeral: as Colin is considering Ben’s counter suggestions, Ben suddenly holds up one finger (in a “Eureka!” gesture) and announces in a rising intonation and louder volume that he has “an idea” (line 740). His pronounced gestures and excitement indicate that his new idea is better than Colin’s idea. Ben’s idea – to show “both ideas” – reflects a shift in his footing: instead of engaging in the conceptual substance of the design mechanism, Ben proposes that they *present* both ideas, referring to his original idea of attaching the hook and Colin’s new idea for a latch attachment, by using two sides of their model (a cardboard box) instead of one. In doing so, Ben shifts his footing to position himself with respect to the classroom expectation – how they will be evaluated during their presentation (*classroom*). Colin’s rising intonation on “Ok” suggests he is questioning Ben’s idea (Schiffrin, 1994), possibly the substance of the idea itself or purpose of showing both ideas, one on either side of the box.

The last three conversational turns (lines 745 – 747) expose salient differences in Colin’s and Ben’s orientations towards the design context, the task objectives, and their positions with respect to the design ideas. When Mary interjects a possible reason for having both ideas (i.e., as an evaluate tool), the boys respond almost simultaneously, but in different ways. Colin agrees, aligning his position with Mary in that using both sides of the box will allow them to compare and evaluate both ideas. His main objective in this task is to devise an optimal solution for the fictional clients, Jamie and Claudia. Ben, on the other hand, responds that they can “do both for the presentation”; by positioning their design activity with respect to the *classroom* framing, Ben moves to preserve his idea of presenting both ideas to their teacher and classmates. The boys’ interaction evidences a mismatch in their schemas with respect to task objectives:

Colin prioritizes criteria that are central to *story* framing, in which he is the evaluator of the design, while Ben prioritizes objectives that are central to *classroom* framing, in which each student's ideas are evaluated by others.

Approximately ten minutes after the previous excerpt, Ms. M. approached the group to ask how their design worked. As they described the design, they pointed out how it would be different in a life-size version. When Ms. M. told them that they could make a life-size version in the classroom, the students excitedly began to gather materials and plan out their design. They attached a hook to the ceiling, and looped a rope through the hook. They then tied a small box containing coins to one end of the rope, and connected the other end to a latch they made, which was attached to a shelf.

As they constructed their "life-size" prototype, the students iterated by varying string lengths, hook heights, box weights, and holding positions. Much of their designing, in these moments, were coded as *making*. Their discourse reflected consideration of materials, specifically how to connect components, cut string, use money as a prop, and attach a hook to the ceiling. Within local *making* stabilities, they considered trade-offs with different materials (e.g., types of hooks), controlled independent variables and varied others (e.g., lengths of string and size of box), tested for functionality, and evaluated the mechanical aspects of the design. Importantly, their stability in *making* framings did not preclude considerations of *classroom* and *story*. Similar to the first excerpt, in which students were stable in an overarching *story* framing but still considered aspects of *classroom* and *making*, their stability in their overarching *making* framing at times included aspects of *story* and *classroom*, particularly when making assumptions and design decisions.

Testing and Presenting Solutions to Class (Day 3)

On the third and final day of the project, each group presented their designs to the class and were given an opportunity to ask each other questions. In the following episode, Colin, Ben, and Chico are presenting their design. Allie was absent during this time. In the front of the room, the group used the box to show their design concept to the class. They then moved to the side of the room, where they had fabricated their life-size prototype to show how it would work.

Our coding of the data indicates that the students' framings involve *story*, *classroom*, and *making* aspects; and upon closer examination, subtle transitions emerge as they are co-constructing framings of this situation. As the students are presenting their design to the class, they collectively share an overarching framing that has them acting as presenters in the classroom, a ritualized *classroom* experience. Within the *classroom* framing, they physically position themselves around their design, and at times act as characters (*story*), to demonstrate and explain how the design will solve the characters' problem of staying hidden. Midway through their presentation (line 1050), the students subtly shift their positioning to articulate specific information from the book (*story*) and concepts they learned in the process of constructing and testing their design (*making*), i.e. specific cause-effect relationships.

Excerpt 3: Students evaluating and presenting design.

line	time			Story	Class	Make
1040	2:51	Colin:	Okay, this is what would happen. [*To Chico*] Cut it.	🟥	🟦	🟩
1041		Ben:	There.			🟩
1042		Colin:	Finally!			🟩
1043		Ben:	That - The money and the night guard.	🟥	🟦	🟩
1044		Colin:	He'd see the money, and he'd also like the box [turns to class] 'cause who wouldn't want a box to keep their money in?	🟥	🟦	
1045	3:29	Ben:	And then Jamie and Claudia would-	🟥	🟦	🟩
1046		Colin:	And then they could run. [*Begins to run*]	🟥	🟦	🟩
1047		Chico:	Then Jamie and Claudia [*Runs with Colin*]	🟥	🟦	🟩
1048	3:33	Ben:	And he (the guard) would pick up their money...[*gestures to show guard picking up money*]	🟥	🟦	🟩
1049		Chico:	Run into the room they're supposed to.	🟥	🟦	🟩
1050		Colin:	And then run into the Balcony Lounge.	🟥	🟦	🟩
1051		Ben:	And (the guard) would keep walking. [*Enacts guard walking*]	🟥	🟦	🟩
1052	3:41	Colin:	[*Turns to audien*ce] We included the Balcony Lounge.	🟥	🟦	
1053		Ben:	[*Turns to teacher*] And we also figured something out. The higher up the box is, the longer they'll have to run and they'll have more time. So if the box is really low, they wouldn't have as much time, but if it was, um, really high, they would have more time to, to escape the clerk.	🟥	🟦	🟩

The students, in this excerpt, begin their demonstration when Colin announces to the class that they are about to show "what would happen" (in the story) when Jamie and Claudia cut the string, and tells Ben to cut it. There is then a moment (lines 1041 - 1042) when the students have trouble cutting the string, and temporarily background the *classroom* and *story* framing while they attend to the mechanics (*making*). When they cut the string and the box falls, the design is set in motion. Colin, shifting back into presenter mode (*classroom*), narrates the sequence of events in the story that constitute their designed system (*story*): he looks to the box, describing that the guard would "see the money," adding that he would also like the box, and then begins to describe what Jamie and Claudia would do ("And then Jamie and Claudia would-"). Before finishing his sentence, Colin stands up straight and begins to run, acting as Jamie or Claudia ("And then they could run"). Chico, spontaneously colluding with Colin's framing, jumps behind Colin and begins to run with him, adding “Then Jamie and Claudia”). Ben, meanwhile, bends down to pick up the money, swinging his elbows to act as a strolling guard, and narrates that the guard would “pick up their money.” As he does so, Colin and Chico run to a specific place in the classroom, announcing that Jamie and Claudia would run to the “room they’re supposed to,” the “Balcony Lounge.”

As the students present their design, they share an overarching stability in a *classroom* framing; specifically, they share a sense of doing a classroom presentation, a familiar classroom activity that involves communicating important information to their teacher and classmates. Within their larger frame, the students coordinate multiple aspects of the *story* and *making* framings in ways that allow them to meet multiple objectives. In lines 1044 – 1048, they animate a coherent interactional arrangement between Jamie, Claudia, and the guard; by embedding animated interaction within their presentation narrative, the students seamlessly show how their design will function for Jamie and Claudia (Goffman, 1981). In Goffman’s (1981) terms, they “parenthesized” the animated interaction within the larger presentation framing (*classroom*): the students kept their audience on hold, or “in abeyance,” (Goffman, 1981, p. 155) as they “dexterously jumped” between acting as the characters to demonstrate their solutions (*story*) and narrating how the design functions (*making*).

When Colin arrives at the Balcony Lounge (line 1052), he stands up straight, turns to the teacher and other students, and announces that he and his group members “included the Balcony Lounge.” In this shift, Colin breaks out of their shared framing; rather than showing the functional aspects of the design in the story context (*making*), he communicates that they included specific information about the story (*classroom* and *story*). Colin's declaration of the Balcony Lounge location triggers a corresponding shift in Ben's framing (line 1053): no longer acting as the guard, Ben also stands up straight, turns to face his teacher, and announces that they "figured something out." He then describes the time-distance relationship that they explored in constructing their design: the higher the box (height from ground), the longer it will take to fall to the ground, and the longer the characters will have to escape the night guard. Still in an overarching *classroom* framing, Ben communicates what he has learned about how things function (*making*) with respect to the story setting (*story*); this is a subtle shift from when we was blending *story* and *making* framings during the presentation to demonstrate the functional solution.

Similar to the previous excerpt, the students' animated interaction is evidence of blended *story* and *making* framings, occurring this time within the structure of a classroom-based activity (*classroom)*. After demonstrating how the design would work in the story *for* and *as* the characters, the students subtly shift in their footing to disclose information that they included *about* the story (i.e., specific information related to the Balcony Lounge) and the specific concepts they learned (i.e., the relationship between the string length and the time it takes for the characters to run a distance).

Discussion

Throughout their design experience, students dynamically shift among and combine their framings of the design situation, drawing from their experiences with interacting with stories, being students in a classroom, and making things work. The data are consistent with previous accounts in which students' framings dynamically interact with their engagement in disciplinary engineering reasoning and acting. For instance, when students attended to the story, they took the characters' perspectives to simulate and evaluate their solution (such as the guard noticing) with respect to particular criteria and constraints. When students prioritized the features and demands of the classroom, they considered how their teacher and classmates would evaluate their project, highlighted specific content to show their knowledge of the book, or presented specific features of their design. And when students focused on the technical aspects of the design, they tested for functionality, considered materials, tinkered with mechanical components, etc.

Our analysis in this study builds on previous work by illuminating nuanced complexities in students' framings: students were not simply framing the activity as having to do with the story or classroom expectations; they were combining and adapting framings *in the moment* to meet local aims, such as meeting clients' needs, the expectations of their teacher and classmates, and the need to develop a technically sound prototype. By attending to the dynamics of student framing, we showed their design process unfold in a series of *in the moment* assessments of what they were doing, and judgments of appropriate epistemic actions to take. In this section, we discuss how particular dynamics of students framing, including combinations of *story*, *classroom*, and *making*, contributed to their organization of epistemic activities. Broadly, we discuss these in terms of the students scoping the problem, co-constructing design ideas, and communicating their optimal design solutions.

Problem scoping. We first see evidence of multiple framings in the early stages of the design task; students "make sense of a messy design situation" (Schön, 1983, p. 40) by bringing multiple schemas of activity to the fore. Like engineers, they begin to scope the problem by identifying a wide range of criteria, including the needs of the characters, the needs for project deliverables, and the need to make something that is functional.

During most of their early designing, the students prioritized understanding the story characters and design setting; they spontaneously took perspectives of characters to understand circumstances (Battarbee, 2004; Kouprie & Visser, 2009), researched the design setting (e.g., printed out maps of the museum floor plan) (Cross et al., 1994), and made assumptions regarding implicit design constraints (e.g., distance to the Balcony Lounge, availability of materials) (Atman et al., 1999).

As the scoped the problem, the students balanced divergent ideating with convergent narrowing to bound the solution space (Dym et al., 2005). Their narrowing of ideas emerged from their need to satisfy multiple framings of the activity: the students interacted with each other's ideas, holding each other accountable to having project deliverables, such as a plan and list of possible solutions (*classroom*), and the need to make a solution (*making*). In this, they collectively negotiated and narrowed the space of possible solutions by “defining, redefining, fabricating, and reconstructing constraints” (Bucciarelli, p. 139, 1994; Christian & Dorst, 1992; Lawson, 1979).

Co-constructing designs. As the students imagined and developed their design ideas, they constructed multiple forms of representation, including sketches, small-scale models, and a life-size prototype. Importantly, the students’ constructions were born from their need to communicate, interact with, and evaluate specific aspects of their design. In the data, we see them framing the activity as *making*, at times evaluating their designs for the story context (*story* framing) and/or considering how to communicate their design to classmates (*classroom* framing). Our fine-grained analysis in the second excerpt shows the complexity of their framing in these moments: the students were not merely shifting from making a physical artifact to considering aspects of both the story and the classroom; they were blending framings, exploiting design representations for the purpose of analyzing and evaluating ideas for story and classroom contexts.

By using their bodies, sketches, and physical objects to stand for entities in the story setting, the students engaged in a “reflective conversation with the design situation” (Schön, 1983; Schön & Wiggins, 1992), in which they could simulate the design solution, interact with their ideas, and explore alternatives. In doing so, they were able to clarify and translate unspecified parameters and clients’ needs into more concrete objectives (e.g., how much time Jamie and

Claudia would need to run and the visibility of the release point from the guard's perspective) (Dym et al., 2005). They then refined their design based on situational feedback. The students' representations, in turn, served as "boundary objects," allowing them access to the design world (in this case, the story) through the physicality of immediate tools (making their prototypes) (Star, 1989).

By using representations, the students were able to bring the conceptual aspects of their design into alignment with each other, such that they could interact in a shared pursuit (Roth, 2001, Star, 1989; Van Sande & Greeno, 2012). Their process of aligning framings resonates with Stevens and Hall's (1998) notion of "disciplined perception." As Stevens and Hall (1998) point out, engineers establish coherence among divergent visions, learning to "see" from and interpret shared focal phenomena through tools and representations. Within shared blended framings, the students, too, exhibited "disciplined perception," exploiting the representational space to communicate and co-construct their design.

Communicating optimal solutions. Towards the end of their design experience, the students were more frequently testing, evaluating, and demonstrating their life size prototype; they spontaneously animated specific characters to test and demonstrate how their design would function in the particular design situation. In these moments, the students coordinated framings to achieve multiple aims: they evaluated functionality for the story setting by animating characters, blending *story* and *making* framings, and demonstrated their design to classmates and teacher within an overarching *classroom* framing.

We see their actions as having productive aspects for learning engineering: in practice, engineers must meet the end user's needs, but must also be able to work within organizational structures (e.g., an engineering firm or company) and be able to communicate their ideas to supervisors in clear and illustrative ways (Bucciarelli, 2002; Dym, 1994; Suchman, 2000). The students' framing, in this case, involved going beyond a traditional class presentation; like engineers, they engaged in "persuasive and constitutive storytelling about the (fictional) future" to their immediate evaluators (Throgmorton, 1996, p. 5).

Conclusion

In this study, we showed that students navigate their own design processes by coordinating multiple framings of the activity. Our fine grained analysis of student discourse showed that their *in the moment* understandings of "what it is that's going on" involved their attention to multiple kinds of things that could be going on (i.e., solving problems for characters, doing a classroom project, making a functional project). To meet emergent design criteria, students managed epistemic activities, such as researching the setting to understand the clients' needs, constructing and testing prototypes, evaluating designs, and iteratively revising their design. Importantly, the students were not engaging in these activities by following a specific design process or predetermined set of practices; instead, their need to engage in these activities emerged in their pursuit of an optimal solution to meet their fictional clients' needs, the organizational requirements of their classroom, and the technical aspects of their designs solution. Our analysis of student framing provided insight for understanding these dynamics: students' *in the moment* assessments of the activity involved their attention to the story, classroom, and technical aspects; and like engineers, they responded by organizing engineering design activities to develop an optimal solution.

Implications

Our empirical account of students doing engineering presents a different view of what engineering involves, and subsequently, a different way of attending to and supporting student engagement in engineering. We argue that students' abilities to coordinate framings – to make *in the moment* assessments of a "messy" design situation and to respond strategically – are a place to focus attention as educators. That is, instead of focusing on students' abilities to memorize and recall specific sequences of design process steps, educators should attend to their abilities to navigate those steps in purposeful ways. In this view, learning in engineering design may involve becoming more sophisticated in one's ability to coordinate framings. Schön (1983) highlights this aspect of engineering expertise in professional accounts: as the engineer "becomes aware of his (or her) frames, s/he also becomes aware of the possibilities of alternative ways of framing the reality of his practice" (Schön, 1983, p. 60), such that knowing in practice becomes ever more tacit and specialized.

We argue that fostering student development involves cultivating an awareness of framings in engineering design and sophistication in ways of organizing them. For students and engineers alike, sophistication comes with experience. In professional settings, the engineer "learns the practice through practicing by learning what to look for and how to respond" (Schön, 1983, p. 60). We believe that the same is true for students – that with structured opportunities, they may develop their abilities to make *in the moment* assessments of design situations and to respond with appropriate epistemic activities. In this, students may develop facility and agency in disciplinary engineering design, becoming ever more skilled at navigating "messy" design situations.

Limitations

Our early findings are promising, however, we acknowledge several limitations to this study. First, we only focus on one group of students participating in one type of project (Novel Engineering). Second, we did not account for the positioning of the teacher or facilitators in their exchanges with students. Third, our data is limited by practical constraints of collecting video data in a classroom, where technology often will not function or capture relevant interactions (Hall, 2000). We plan to extend this study by exploring student framing across multiple kinds of elementary engineering projects, and to examine similarities and differences in students' framings in engineering design. In doing so, we hope to identify both patterns and idiosyncrasies across design process trajectories, and to examine in greater detail the moments in which students transition or adapt their framings in pursuits of different goals. These foci may provide further insight into how students engage in engineering, and will continue to inform the development of instructional practices.

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Chapter 7: Contributions, Implications, and Future Directions

In this dissertation, I examined how students form tacit understandings, or *frame* (Goffman, 1974), Novel Engineering design experiences. In a collection of three empirical studies (Chapters 4, 5, and 6), I showed the complex dynamics of student framing and described the ways in which students' framings involve and are evidence of their engagement in disciplinary engineering design. In this chapter, I reflect on the theoretical and methodological contributions, discuss implications and limitations, and propose future directions.

Theoretical Contributions

As engineering becomes more present in the elementary curricula, there is a greater urgency for advancing research on student learning and methods for analyzing student engagement in engineering design. Research on student learning and engagement in engineering are widely under-theorized in the literature; many scholars in the field call for more expansive research methodologies and diversity in research questions (Borrego, Douglas, & Amelink, 2009; Case & Light, 2011; Johri, Olds, & 2014; Koro-Lundberg & Douglas, 2008). As I describe in the following, my dissertation addresses these calls by advancing theory on the complex dynamics of student framing in engineering, and by shedding light on elementary students' abilities to reason and act as engineers.

Empirical insights from three component studies. Each of the three interrelated empirical studies makes unique theoretical contributions pertaining to student framing in engineering design: Chapter 4 examines students who are stable in their sense of the task; Chapter 5 explores cases in which students' framings shift and evolve as they interact with each other and materials; and Chapter 6 shows students' coordinating framings in the moment as they navigate a design process. In the following, I discuss how students' framings involve their participation in disciplinary engineering. I first review study-specific contributions and then describe crosscutting themes.

In Chapter 4, I examined two students who shared a central objective of designing an optimal solution for their fictional client. To meet their clients' needs, the students inferred design criteria and constraints, made informed assumptions and estimates, co-constructed scaled representations, and defined evaluation criteria. I argued that the students' persistent attention to the story characters involved their stability in framing the task as beginning engineers: they engaged in engineering activities in service of helping their fictional clients.

In Chapter 5, I examined the ways in which students shift and adapt their framings of what is taking place as they interact with materials and artifacts. The data indicated that students' interactions with materials were often pivotal in their framing: in some instances, their interest in material objects triggered deviation from engineering design, whereas in others, they involved complex reasoning for optimal solutions. For example, one group's interactions with craft materials (e.g., pipe cleaners and cardboard) contributed to a change in their reasoning about the design; they dismissed the constraints of the story setting and the need to design functional solutions, opting instead to incorporate fantastical features (e.g., "laser beams" and "mini bodyguards"). This change, I argued, marked a shift in their framing of the activity away from engineering design to include aspects of pretend or storytelling, rather than considering engineering criteria, such as functionality or feasibility.

In other instances, however, I found that students' shifting and evolving framings supported productive engagement in engineering design. For example, I highlighted a particularly transitional moment in which the students considered different materials to use for the roof of a partially constructed dog pen model. Their interactions with model and materials tipped them into thinking not only about the clients' needs in the fictional setting, but also to considering the classroom evaluation criteria – what their teacher, classmates, and researchers might need to understand about their design. That is, the students accounted for both their fictional client (user) and immediate stakeholders (teacher, researchers, classmates); in doing so, they enacted epistemic activities that reflected those of practicing engineers, such as analyzing, perspective-taking, and evaluating for multiple clients.

In Chapter 6, I drew from and extended findings from previous chapters to examine the framing dynamics of one group over the course of their three-day design experience. By conducting a finer-grained analysis of student discourse, I showed that their *in the moment* framings involved their attention to fictional clients' needs, the expectations of their teacher and classmates, and the technical aspects of their design. To address these criteria, students organized epistemic activities, such as researching the setting to understand the clients' needs, constructing and testing prototypes, evaluating designs, and iteratively revising their design. Importantly, their need to engage in these activities emerged in their coordination of framings as they accounted for their fictional clients' needs ("story framing"), the requirements of their classroom ("classroom framing"), and the technical aspects of their designs solution ("making framing"). Like engineers navigating a messy design situation, the students made *in the moment* assessments of the design situation and responded accordingly by organizing engineering design activities.

Productive framings for engineering design. In each of the three studies, I identified different dynamics in student framing that were productive for their engagement in engineering design: in particular, I highlighted (1) stabilities to story, (2) shifting between classroom and story framings, and (3) coordination among multiple framings, including story, classroom, and making. In all of these, I showed different ways that students act and reason as engineers. In Stella and Alexi's stability, they attended to and evaluated for fictional clients; in Jack, Cooper, and Thomas' shifting and negotiating framings, they considered multiple perspectives and discussed how to communicate their design ideas; in Colin, Ben, Chico, and Allie's coordinating framings, they navigated a complex engineering design process to develop a solution. The central finding, that students engage in engineering within and across framings, warrants a larger question: *What do the varying framing dynamics have in common that support students in reasoning and acting as engineers*?

Based on the findings in this dissertation, I argue that students' varying framings involve productive epistemological resources for engineering (Hammer, Elby, Scherr & Redish, 2005; Redish, 2004). That is, their understandings of what is taking place with respect to knowledge and learning have them realizing what they know and what they need to figure out. In this, students organize epistemic activities in pursuit of figuring out how to best solve a problem; they may research design settings to understand clients' needs and constraints, identify potential resources, build, test, and evaluate physical prototypes, and improve as needed. When framing as beginning engineers, students are constructors and evaluators of ideas and solutions, acting as epistemic agents (Scardamalia & Bereiter, 2006), in pursuit of (what they define to be) optimal solutions.

Engineering in pursuit of optimal solutions. In the cases I presented, students did not engage in engineering design steps or practices in directed or sequenced way as the literature suggests they do; instead, they initiated ways of reasoning and acting, or practices, in their pursuits of optimal solutions. For example, when Stella and Alexi were designing a dog pen, they generated a sketch with an appropriate "life size" scale. The girls, in this instance, were not sketching or scaling their sketch because it was a step in the design process; they co-constructed a detailed sketch in service of designing a dog pen that would be an appropriate size for Marty and Shiloh.

For Stella and Alexi, designing an optimal solution involved meeting their fictional clients' needs. In other cases, however, students' sense of optimal emerged as they coordinated multiple framings. For example, as I showed in Chapter 6, as students were scoping the problem, they considered their fictional clients' needs and the design setting (story), the availability of resources in the classroom (classroom), and ensuring functionality (making). As they coordinated framings of the activity, they negotiated the different criteria and constraints of the design task, and more narrowly defined the problem. In doing so, they enacted engineering design "steps" or practices (e.g., researching the design setting, asking questions, and brainstorming possibilities) in pursuit of achieving framing-specific criteria (i.e., meeting clients' needs, classroom requirements, making a constructible design). The students, in this instance, invoked engineering practices in service of meeting their fictional clients' needs, the organizational requirements of their classroom, and the technical aspects of their designs solution. That is, their coordination of framings involved navigating an engineering design process to develop an optimal solution that would meet multiple design criteria.

This collection of empirical accounts of students doing engineering presents a different view of what engineering involves, and subsequently, a different way of attending to and supporting student engagement in engineering. I have identified and described varying dynamics in student framing, focusing on how their framings involve and are evidence of productive engagement in engineering design. Based on these accounts, I argue that attention to student framing should be a focus in engineering education. Instead of honing students' abilities to memorize and recall specific sequences of design process steps, I argue for attending to and supporting their abilities to coordinate multiple kinds of activities in engineering design and to navigate context-specific design processes in purposeful ways.

Methodological Contributions

Many of the current research methodologies target simple measures to capture students' designing skills (see Chapter 1). These measures often do not reflect the dynamic and responsive nature of engineering in professional accounts, nor do they capture the nuance and complexity in students' design activities. In this dissertation, I bridged disciplinary engineering research and learning sciences to understand how students make sense of open-ended engineering design activities.

Examining students' engineering abilities *in situ*. To investigate different dimensions of Novel Engineering design experiences, our research team videotaped students and teachers during activities. By capturing interactions on video, we were able to participate in cycles of video-watching, formulating analytic foci, addressing emergent domain-specific questions, and drawing from a wide array of theoretical foundations to understand patterns and idiosyncrasies. Collaborative viewing played a particularly powerful role in this approach; by holding each other accountable to "staying close to the data," we elicited each other's preconceived notions and tendencies to draw theoretical abstractions or apply generalizations (Geertz, 1973; Jordan & Henderson, 1995), and stayed close to the data.

Drawing mainly from an interactional analysis approach (Jordan & Henderson, 1995), I (as part of the research team) investigated phenomenological aspects of student framing in Novel Engineering design activities, particularly the dynamics through which students form a sense of the activity in socially and materially rich classroom settings. In my analyses, I considered what the data suggested with respect to how students make sense of open-ended, ill-structured design situations, and how their reasoning and actions reflect expert practices in ethnographic accounts. This approach is, in itself, a contribution to engineering education; by and large, the more common method is to compare novices and experts (see Atman et al., 2007; Crismond & Adams, 2012), often in decontextualized interview-based protocols, for the purpose of examining data for differences that separate novices from experts. In this work, I highlighted productive ways students reason and act as beginning engineers by examining their discourse, actions, and the substance of their reasoning as they engaged in design activity.

Methods for analyzing framing in engineering. In the collection of empirical studies, I recruited a range analytic tools and developed markers to capture emergent phenomena at varying scales and grain sizes. These tools and markers contribute to literature in both engineering education and framing in classroom settings by elucidating methods for analyzing student framing in classroom-based engineering activities.

- *Analyzing framing stabilities and instabilities*: As our research team iteratively analyzed video data from one classroom, we noticed differences in student engagement: some would stick to their understanding of the activity and others would fluctuate or adapt their understandings. In Chapters 4 and 5, I identified analytic markers in the data to show evidence of stability and instability in student framing. For instance, markers of stability involved persistence in students' attention and dismissal of competing expectations. In comparison, evidence of instability involved shifting from talking about the story to listing vocabulary words.

- *Characterizing emergent framing patterns*: Over the span of three years, our research team had identified two prevalent patterns in students framing: "story" and "classroom." In the data, we identified evidence of these framings by attending to what students thought the task was about, i.e., when they were focused on the story and their fictional clients, and when they prioritized classroom criteria. In Chapter 6, I drew from previous analyses, observational accounts, and *in situ* experiences to codify emergent framing patterns. I established evidence of framing patterns by examining one group of students throughout their design experience and coding for how they were taking up the activity on a turn-by-turn basis. Through iterative coding and video-analyses with other researchers, another pattern in student framing emerged, occurring when students' attention to the task was mainly on figuring out how to make something work. While this pattern crystallized in the analysis of one group, my conjecture is that students are often framing engineering activities as "making things work."
- *Varying grain size:* In applying coding to data, new complexities emerged: the data indicated that students, in some instances, were framing the activity in multiple ways, and often in different ways than their group

members. To understand the data, I conducted discourse analysis on a finer grain size and examined students' positioning of their ideas with respect to particular framings of the activity and to each other. In doing so, I was able to gain insight to how they coordinated and blended different framings of the activity, as well as how they co-constructed shared framings.

- *Coordinating scales:* To interpret one group's collective framing over the course of their design experience, I examined the coded data from a "zoomed out" perspective[16]. By doing so, I was able to gain insight to local coherences (marked by consecutive turns of the same framing), which I interpreted to be evidence of students' framing stabilities, and negotiations of framings (toggling framings on a turn-by-turn basis). Moreover, the coded data illustrated how a group's framings unfold throughout their design experience. For instance, the data indicated that students were comparatively more stable in framing the task as engineering for story characters in the beginning than they were later in the task.

Pedagogical Implications

For instruction, the diverse and complex ways students frame open-ended engineering design experiences raise many questions related to lesson structures, response moves, and fostering productive engagement in engineering design. In this section, I focus on a central pedagogical challenge that arose in this work:

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[16] As I discuss in Chapters 2 and 3, I assume a dynamic unit of analysis to examine phenomena of interest. Here, the analytic method of "zooming" is appropriate to examine phenomena at varying levels (Conlin et al., 2010; Mandelblit & Zachar, 1998; Roth, 2001).

managing open-endedness in engineering design situations. I argue that further research is needed to understand instructional design and practices, particularly around sustaining student agency, while fostering their abilities to develop optimal, functional design solutions.

The complexity of open-endedness. In open-ended design activities, especially those that involve craft materials (e.g., cardboard, tape, glue), students may frame the activity as making dioramas, storytelling, pretend play, etc. In this occurrence, students' understandings of "what counts" as a representation may influence their sense of "what counts" as engineering; they may create dioramas of a fantastical solution instead of prototypes that are functional and feasible for clients. On the other hand, in tightly constrained and defined design tasks, students are prevented from experiencing the "messy" nature of disciplinary engineering design. Further, in well-defined design tasks, students may frame the task similarly to how they frame a spelling test: they might expect there to be one right way of solving the problem and one right solution, and may focus on how they are evaluated as students rather than acting as evaluators of their own designs (see Chapter 4). Thus, the main challenge for educators is to sustain student agency while appropriately bounding open-endedness for students learning engineering design, such that students have opportunities to navigate design situations, but recognize the need to adhere to design contexts and constraints.

Implicit ambiguities for students. In the following, I describe aspects of Novel Engineering design activities that may play a pivotal role in students' framings. I then discuss “share-outs” as a classroom-tested strategy to support students in managing open-endedness.

- *Materials and representational aspects of design*: As students create engineering sketches, models, and prototypes, they are also learning the purpose and utility of representations in engineering design. That is, they are learning to use materials to stand for elements of their design concepts so that they can communicate, test, and evaluate their ideas. In students’ everyday dealings with craft materials and representing things (e.g., book reports), it is acceptable to find attractive materials and to imagine referent entities, usually having to do with the physical salience of the object itself (a pipe cleaner could become a “laser beam”). In classroom based engineering activities, these kinds of assumptions could shift students’ sense of the task and their objectives.
- *Managing the scope of imaginative technologies*: While the laser beam example is clearly not engineering, there are other occurrences in acts of representing that are more blurry with respect to “what counts” as engineering. For instance, students may use objects or aluminum foil to represent technologies they know to exist (advanced smart phones, gadgets) as a part of their solution. This is something engineers do often: when prototyping a new phone, an engineer may place a representational screen on a prototype to show where it will be, perhaps while conveying a design idea for a new durable material and design. The engineer uses representational entities to stand for elements that he or she does not have

(or need!) for the purpose of conveying a design idea. While students may make similar assumptions in productive ways, representing components that they do not have access to, they may also imagine and represent technologies as their final solutions (i.e., a *deus ex machina* solution), such that they do not need to engage in engineering to develop functional prototypes.

- *Inaccessible design contexts*: For Novel Engineering design activities, and many other engineering activities, the design context is not physically accessible. Further, the design context may have different physical laws and realities (e.g., magical qualities, talking animals). A challenge that may come of this is determining what counts as a functional solution; what may be functional in the story may not be functional in the student's reality. For students, developing a "magic" solution that obeys the governing rules of the design context (or book genre, in this case) may seem acceptable; that is, their designs achieve verisimilitude of particular realities. For instructional purposes, however, this may present challenges in fostering students' abilities to test and evaluate functional design solutions. It also may create tensions between literacy and engineering goals: in creating functional solutions in the classrooms, students may need to deviate from the story setting, plot, character abilities, etc.

Share-outs as a strategy to manage open-endedness. Across classrooms and activity structures, our research team has noticed advantages in teacher-structured "share-outs" during Novel Engineering activities. In classroom share-outs, each student group has an opportunity to tell their classmates and teacher about the problems they are solving, their design ideas and solutions, and their design processes. The students then have an opportunity to respond to their classmates' questions or comments from their classmates.

In these class-wide discussions, students' implicit assumptions regarding "what counts" as an engineering solution often emerge. To reconcile differences among their assumptions, students may need to collectively negotiate and establish design criteria pertaining to functionality, design constraints, and meeting the needs of characters. We have noticed particular kinds of questions that help students tune in to each other's framings of the activity. These questions include the following:

- What counts as an engineering design solution: *Does it have to be functional? Does it work within the setting of the story?*
- Students' assumed relationships to characters (Are they designing *as* characters, or are they acting as consultants to design *for* characters?): *Do the characters have access to tools and materials?*
- How to represent solutions: *What do specific materials stand for in the story setting? Is it ok to represent technologies they know exist to convey a design idea?*
- What are the relevant problems in the story: *Do the solutions address a main problem? Is it a problem that can be solved by engineering?*
- How to test and evaluate design ideas: *How do you know it works? How are you testing it? How would it work in the story setting?*

Teachers may initiate design share-outs at different points in the process, and may decide to include more than one share-out during a Novel Engineering activity. As students become more practiced at defining and holding each other accountable to meeting engineering design criteria, they may be more inclined to frame the task as a community of beginning engineers.

Limitations

Context-based. Like all projects, there are practical and methodological limitations to this work. Most prominently, this work is limited in the sense that it takes place in one type of engineering design experience (Novel Engineering) that involves engineering in a literature-based context. While the Novel Engineering project provided a rich and diverse set of classroom contexts and activities from which I drew data, there is certainly much to be learned from other types of engineering design projects. For instance, do students enact different forms of reasoning when engaging in closed-ended or more tightly-constrained engineering design projects? Similarly, how are students' ways of evaluating their designs different when the design context is not a literature-based setting, such as when they are solving authentic problems and/or have access the actual context, such as their school or classroom? This is a rich area for future research.

Methodological. There are, of course, methodological limitations to this work as well. The first limitation is in the collection of useable data for the project. While we were able to collect hundreds of hours of video, much of the data could not be used due to lack of informed student or parent consent, malfunctioning technology (e.g., inaudible, shaky cameras), or interference during taping (e.g., researchers, teachers, or students moving cameras). Second, there are inherent limitations in using video to as data (Hall, 2000), which is, in itself, "theory-laden."

Hall (2000) describes the types of decisions researchers make regarding choice of data to show, selection of contextual features to include, and reorganization and descriptions of original phenomena, which are necessarily shaded by researchers' perspectives. Brown (1992) refers to the confoundedness of data selection as the "Bartlett Effect," (p. 162). She describes that as researchers select portions of edited transcripts to illustrate a theoretical point, they are drawing a small sample from a larger database, and their selection is obviously going to buttress the researchers' theoretical stance and argument. The problem, then, is that the researchers only select the segments that prove his or her point. Schoenfeld's (1992) method of mitigating this problem is for researchers to provide enough raw data to readers so that they can make sense of it themselves under less influence from the researchers' lens[17].

In Chapter 6, I apply this mitigation technique by accounting for all data on one group's activity and disclosing appendices with specific sections of data that proved to be ambiguous in our analyses. My hope is that by disclosing both the data and our reasoning about the data, we may spark conversation among other engineering education researchers regarding how students make sense of

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Many have argued that it is highly impractical in some cases to keep all data (and videotapes, field notes, transcripts) on file to later be checked by an "indefatigable sleuth" (Brown, 1992, p. 162). However, when providing transcripts for coding, I do agree that providing enough transcript for readers to reconstruct the code is necessary (Hammer & Berland, 2013; Schoenfeld, 1992).

engineering design tasks and what counts as evidence of their engineering abilities.

Recommendations for future work

In this study, we illustrated the complex, nuanced dynamics of student sense-making within a materially-rich classroom setting, and shed light on students' productive beginnings in engineering design. These findings, however, only skim the surface of a vastly unchartered field of elementary engineering education, and warrant deeper research into the dynamics of student engagement. Further research will not only provide insight into students' abilities for engineering, it will also inform the development of instructional practices and curricula, and empower educators to identify and respond to students' engineering reasoning in both formal and informal learning experiences. In the following, I provide a list of possible research directions.

Diversifying research contexts and engineering activities. Future work may include investigating the dynamics of student engagement in multiple kinds of engineering design activities, such as service-based or more tightly constrained challenges, and across a wider range of demographics. For instance, one possibility is to analyze the Engineering is Elementary corpus of data. There are likely to be many differences between Novel Engineering and Engineering is Elementary data; however, my conjecture is that we may find common themes in students' abilities for engineering, such as stable engineering epistemologies, as they are engaging engineering activities that have varying degrees of constraints and structure. We may also find unique affordances of more structured tasks, such as students' persistence in achieving solutions that are optimal in technical aspects (functionality, efficiency, structural integrity, etc.).

Characterizing progress in learning engineering design. In this dissertation, I document *in situ* accounts of students' beginning engineering design abilities. While these accounts show that students have abilities for engineering, they do not speak to students' development of engineering abilities. These findings give rise to a larger question pertaining to engineering education: *What does progress look like as students are learning engineering design*?

Based on this dissertation and findings in science education, my inclination is to identify progress along two related dimensions. The first, which I highlighted as theoretical contribution in this work, involves stability in students' productive epistemologies in engineering. In this view, students recognize what they know, what they need to know, and maintain a stance towards *figuring things out*; when engaging in engineering design, they act as constructors and evaluators of ideas and artifacts.

The second related dimension of progress is a development and awareness of engineering frames, and an ability to coordinate them in pursuit of design solutions. In this, progress in student learning may involve developing facility and agency in managing engineering practices and strategies to achieve local and global design objectives.

Exploring student resources for engineering design. While I touched on productive student engagement in terms of their epistemic and social strategies, there is still much to be learned about the wide array of epistemic and social resources students bring to bear in engineering design tasks. Another potential direction for future research is to expand research methodologies to conduct more comprehensive microgenetic accounts of students' cognitive abilities, or engineering habits of mind, across groups and settings, and sociogenetic accounts of processes or patterns across multiple events.

Instructional approaches. Another area for future work is in the development of instructional theories and approaches for teaching engineering. This research would involve examining and reflecting on aspects of the activity structure, teacher orchestration, or student interactions that led to students' productive disciplinary engagement, and articulating themes to support or foster student engagement in engineering. Doing so might also raise questions around appropriate scaffolding of student learning in engineering, and maintaining the delicate balance between sustaining students' agency and helping them achieve their epistemic goals.

Concluding Thoughts

In this dissertation, I explored the complex and nuanced dynamics of student framing in open-ended, ill-structured design situations. In doing so, I documented a wide array of students' nascent abilities for engineering design, and showed the dynamic ways students invoke these abilities in their pursuits of optimal solutions.

This work comes at a critical time: as new reports and standards call for engineering design at an elementary level, there is a pressing need to know what engineering looks like at an elementary level and how to foster student learning in disciplinary engineering. More specifically, there is a need for research to shift from focusing on how to teach students what they *don't* know about engineering to understanding the sophisticated abilities they *do* have – students' productive beginnings in engineering. With informed approaches to teaching engineering, we may be better equipped to support budding engineers in developing technical know how, while cultivating their abilities to engineer solutions with imagination, creativity, and care.

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