Iteration in Early-Elementary Engineering Design

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Abstract

K-12 standards and curricula are beginning to include engineering design as a key practice within Science Technology Engineering and Mathematics (STEM) education. However, there is little research on how the youngest students engage in engineering design within the elementary classroom. This dissertation focuses on iteration as an essential aspect of engineering design, and because research at the college and professional level suggests iteration improves the designer's understanding of problems and the quality of design solutions. My research presents qualitative case studies of students in kindergarten and third-grade as they engage in classroom engineering design challenges which integrate with traditional curricula standards in mathematics, science, and literature. I discuss my results through the lens of activity theory, emphasizing practices, goals, and mediating resources. Through three chapters, I provide insight into how early-elementary students iterate upon their designs by characterizing the ways in which lesson design impacts testing and revision, by analyzing the plan-driven and experimentation-driven approaches that student groups use when solving engineering design challenges, and by investigating how students attend to constraints within the challenge. I connect these findings to teacher practices and curriculum design in order to suggest methods of promoting iteration within open-ended, classroom-based engineering design challenges. This dissertation contributes to the field of engineering education by providing evidence of productive engineering practices in young students and support for the value of engineering design challenges in developing students' participation and agency in these practices.

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For the scholars. To my advisor, Bárbara, and my committee members, Chris, Brian, Janet, and Johannes: thank you for your time, wisdom, and unending patience; To Kirsten and Merredith: thank you for the mentorship and guidance. To Morgan, Ethan, Magee, Elissa, and everyone at the CEEO: thank you for making so much stellar research and outreach possible. To Aaron, Cynthia, Katie, Mary, Jessica, Jennifer, Ying, Kathleen, Chris, and all those students ahead and behind me: thank you for friendship and scholarship. To LEGO Education and to my research school: thank you for this fantastic opportunity, and for sharing your commitment to engineering education with me. To my colleagues and students in the classroom at Belmont High and NCSSM: thank you for helping me know what I didn't know about teaching. To Mr. Whitford, Ms. Salter, Ms. Williford, Mr. Miller, Mr. Reaney, Dr. Reynolds—and especially Mr. Little and Ms. Honeycutt, who are greatly missed: I hope the flock of educators you shepherded does justice to the dedication you showed us in your classrooms.

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For nearly 8 years, I reflected upon my experiences in graduate school. But then one night, I found the essence of the PhD in a bedtime story:

> "When you are a Bear of Very Little Brain, and you Think of Things, you find sometimes that a Thing which seemed very Thingish inside you is quite different when it gets out into the open and has other people looking at it."
>
> – Winnie-the-Pooh

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Introduction

Lessons incorporating engineering design challenges are being enacted in the youngest K-12 classrooms; despite this, studies on early childhood engineering practices and pedagogy are largely absent from the engineering education literature. As part of a project headed by the Tufts University Center for Engineering Education and Outreach and LEGO® Education, this dissertation investigates how young elementary students engage in engineering design practices related to iteration as part of a classroom activity system. Within this project, I choose to focus on practices related to iteration, as iteration is regarded as a distinctive feature of engineering design (Adams, 2001; Katehi, Pearson, & Feder, 2009) and research with college students and professionals has shown iteration promotes a higher quality of final solutions and a better understanding of the underlying concepts within a design (Adams, 2001; Atman et al., 2007; Atman, Cardella, Turns, & Adams, 2005). I observed four classroom lessons, created and enacted with my assistance by teachers selected from the research program, showcasing six student groups. Borrowing from situative cognition and activity theory, I considered the resources of the classroom activity system—including students, teachers, materials, and the lessons themselves—for promoting engineering practices related to iteration. From video, observational data, and classroom artifacts, I constructed case studies through the use of narrative summaries and illustrative examples of student practice, detailing the practices of students and teachers within the classroom context. My goal was to answer questions about three aspects of student practice: student approaches to ill-defined engineering design challenges, how classroom resources provide affordances for thinking about constraints, and the ways in which classroom contexts impact the evaluation and revision of design solutions.

Current Research and Standards in K-12 Engineering Education

The foundation of this research lies in the reformation of Science, Technology, Engineering, and Mathematics (STEM) Education to emphasize the interconnectivity of these disciplines. Once marginalized and ignored in the K-12 curriculum (Bybee, 2011), engineering is now promoted as a missing link. It is touted as having the power to connect content in mathematics and science through emerging technology by situating learning in problem-based lessons and engineering design challenges (Brophy, Klein, Portsmore, & Rogers, 2008). The practice of engineering design, akin to science inquiry, is becoming an increasingly common addition to K-12 science and technology standards at both the national and state level (American Association for the Advancement of Science, 1993; International Technology Education Association, 2007; National Research Council, 2011, 2013; *Science Standard Course of Study and Grade Level Competencies*, 2004). Despite engineering design's extensive nation-wide and state-wide support, there is a lack of research or consensus on best practices for incorporating engineering into the early grades (Katehi et al., 2009).

The practice of engineering design has been studied at length at the college and professional level, but much less so at the K-12 level. A National

Academy of Engineering (NAE) report *Engineering in K-12 Education: Understanding the Status and Improving the Prospects* (Katehi et al., 2009) concluded that there are several gaping holes in what is known about the field of pre-college engineering education. They found: "no reliable data on the precise number of United States (US) K-12 students who have been exposed to engineering-related coursework" (Katehi, et al., 2009, p. 6); "no widely accepted vision of what K-12 engineering education should include or accomplish" (p. 7); no attempt within the research community "to specify age appropriate learning progressions in a rigorous or systematic way" (p. 8); and the most salient to my interests, a lack of research characterizing what engineering-design skills K-12 students already possess:

> To understand the engineering process, K-12 students must learn not only engineering concepts, but also necessary skills. In their integrative review of research results on the development of core engineering skills in K-12, the commissioned authors focused on skills related to design and redesign, which are the prototypical engineering processes (Petrosino, Svihla, & Brophy, 2008). The necessary skills include defining the problem, specifying requirements, decomposing systems, generating solutions, drawing and creating representations, and experimenting and testing. Because empirical evidence about how students develop most of these skills is limited, the commissioned authors could only glean evidence on the latter two topics, the development of drawing and representational skills and experimentation and testing skills. (Katehi, et al., 2009, p. 133)

The NAE report suggests our current implementation of K-12 engineering education in the US is haphazard and lacks a foundation in research. In their opinion, we are operating with scant knowledge about our students' understanding of engineering and the design process.

Engineering is a two-fold discipline, consisting of both a knowledge base, and also a process for applying the domains of mathematics, science, and technology to solve human problems (Katehi et al., 2009). As engineering has been folded into K-12 science standards, there is a pointed emphasis on practice rather than content (Bybee, 2011; Cunningham & Carlsen, 2014). As Cunningham and Carlsen (2014) point out, what differentiates chemistry from chemical engineering is not the content, but the goals and practices. It is this commonality that the latest STEM standards are attempting to exploit with the addition of engineering design alongside science inquiry. The *Next Generation Science Standards* (2013) and the National Research Council's (NRC) *Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (2011) similarly employ the term "practices" in reference to both inquiry and design, and as the *Framework* explains,

> We use the term "practices" instead of a term such as "skills" to emphasize that engaging in scientific investigation requires not only skill but also knowledge that is specific to each practice. (p. 30)

The NRC-funded *Ready, Set, Science!* (Michaels, Shouse, & Schweingruber, 2007) explicates this further by stating,

> Science practice involves doing something and learning something in such a way that the doing and learning cannot really be separated. Thus "practice" ...encompasses several of the different dictionary definitions of the term. It refers to doing something repeatedly in order to become proficient (as in practicing the trumpet). It refers to learning something so thoroughly that it becomes second nature (as in practicing thrift). And it refers to using one's own knowledge to meet an objective (as in practicing law or practicing teaching). (p. 34)

This is all to say that standards are shifting toward a future where assessment will evaluate students' understanding of ideas in tandem with their abilities to participate in the practices of science to answer questions about the natural world, or the practices of engineering to solve human problems (National Research Council, 2013). In light of this, my research will examine learning via student activity in the classroom, rather than decontextualized student knowledge.

Engineering Practices in Elementary Classrooms

Whether referred to as engineering *behaviors*, *strategies*, *skills*, *activities*, or *steps*, various practices have been compiled into cyclical representations of the engineering design process (see Figure 1), as well as lists (such as those found in the *Next Generation Science Standards*, 2013; see Figure 2) and matrices (see Figure 3; Crismond & Adams, 2012). Diagrams of the engineering design process are static and circular, synthesized and simplified representation of the practices professional engineers follow when solving an engineering problem (Sheppard, Colby, Macatangay, & Sullivan, 2006; Stevens, Johri, & O'Connor, 2014;

Trevelyan, 2013). Perhaps the most ubiquitous representation (see Figure 1) at the elementary level was popularized by the *Engineering is Elementary* (EiE) curriculum out of the Museum of Science in Boston (Cunningham & Hester, 2007), featuring a five-step engineering design process: *Ask*, *Imagine*, *Plan*, *Create*, and *Improve*. These steps can be thought of as metapractices, incorporating several practices together toward some purpose. In Figure 1 below, for example, *Create* includes both consulting a plan to build a solution, as well as testing the solution against the previously-established design constraints. Models of the engineering design process have ranged from a reduction of the cycle to simply *analysis, synthesis, and evaluation* (Cross, 2000), to expanding the process out into as many as eight or more steps, which students are often asked to memorize and reproduce on standardized tests (Massachusetts Department of Education, 2006). The most important take-away from this is that there exists no standardized engineering design process, nor definitive list of engineering practices, at the K-12 level.

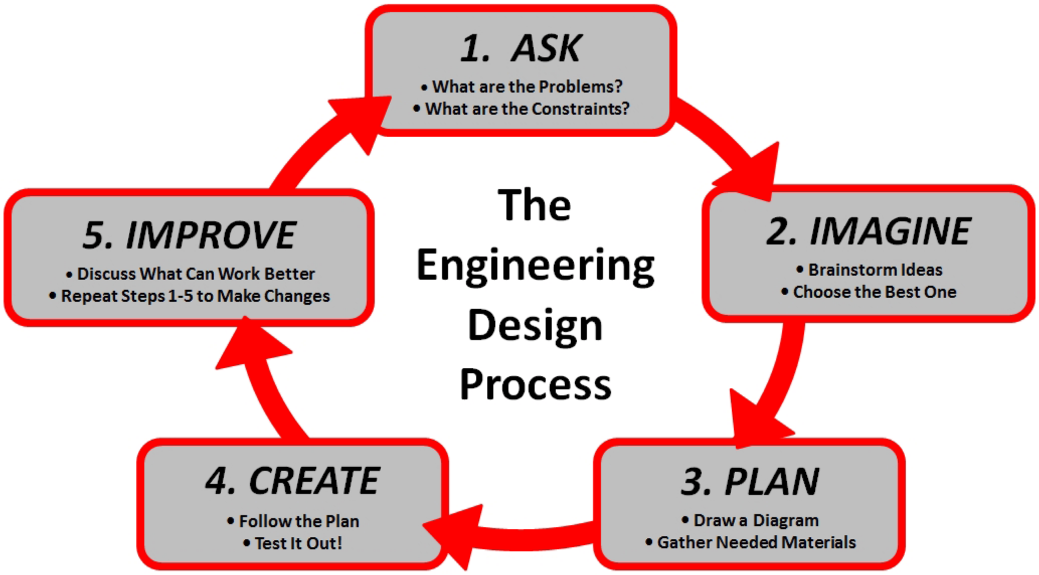

Figure 1. The cyclical Engineering Design Process as modeled for younger students by the *Engineering is Elementary* (Cunningham & Hester, 2007) curriculum.

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

Figure 2. Next Generation Science Standards (2013) science and engineering practices.

Design Strategy	**Beginning Designer Patterns**	**Informed Designer Patterns**
Understanding the Challenge	Treat design task as a well-defined, straightforward problem that they prematurely attempt to solve.	Delay making design decisions in order to explore, comprehend, and frame the problem better.
Build Knowledge	Skip doing research and instead pose or build solutions immediately.	Do investigations and research to learn about the problem, how the system works, relevant cases, and prior solutions.
Generate Ideas	Work with few or just one idea, which they can get fixated or stuck on, and may not want to change or discard.	Practice idea fluency in order to work with lots of ideas by doing divergent thinking, brainstorming, etc.
Represent Ideas	Propose superficial ideas that do not support deep inquiry of a system, and that would not work if built.	Use multiple representations to explore and investigate design ideas and support deeper inquiry into how system works.
Weigh Options and Make Decisions	Make design decisions without weighing all options, or attend only to pros of favored ideas, and cons of lesser approaches.	Use words and graphics to display and weigh both benefits and tradeoffs of all ideas before picking a design.
Conduct Experiments	Do few or no tests on prototypes, or run confounded tests by changing multiple variables in a single experiment.	Conduct valid experiments to learn about materials, key design variables, and how the system works.
Troubleshoot	Use an unfocused, non-analytical way to view prototypes during testing and troubleshooting of ideas.	Focus attention on problematic areas and subsystems when troubleshooting devices and proposing ways to fix them.
Revise/Iterate	Design in haphazard ways where little learning gets done, or do design steps once in linear order.	Do design in a managed way, where ideas are improved iteratively via feedback, and strategies are used multiple times as needed, in any order.
Reflect on Process	Do tacit designing with little self-monitoring while working or reflecting on the process and product when done.	Practice reflective thinking by keeping tabs on design strategies and thinking while working and after finished.

Figure 3. K-12 and Post-Secondary Engineering "strategies" from Crismond and Adams' (2012) *Informed Design Teaching and Learning Matrix.*

One implication of the simplified model of engineering design seen in Figure 1 is that teachers use the 5-step engineering design process to structure lessons for their class, guiding students through the process, step by step, sometimes scaffolded through the use of worksheets or by partitioning the lesson into "planning time," and "building time," and "testing time." McCormick (2004) does report that novice teachers presented with this simplified form of engineering practice tend to treat design as formulaic, and emphasize following the process over engaging in, and deeply understanding, the practices themselves. Cunningham, the creator of the EiE curriculum, has written that the language used in national K-12 standards runs the risk of encouraging educators to mistakenly treat engineering practices as content rather than skills, akin to an understanding of the water cycle rather than participation in science inquiry (Cunningham & Carlsen, 2014). If engineering design is something students "do," not something students "know," then student understanding of engineering cannot be assessed by asking students to list the steps of the engineering design process or recite the definition of “planning." Engineering assessment and research must center around observing students engaged in the practice of designing.

Crismond and Adams (2012) attempted to organize the corpus of engineering education research through a meta-literature review of design studies, culminating in the creation of an integrative framework of student practices and teaching suggestions, the *Informed Design Teaching and Learning Matrix.* This *Matrix* (see Figure 3) proposes evidence of patterns of design strategies on a continuum from novice (beginning designers) to not-quite experts (informed designers), which they theorize is exhibited by K-16 engineering students. However, the *Matrix* only provides examples of practices from each extreme end and not the entire continuum, and most of the data the authors cited as examples of beginning designers' practice were not drawn from investigations at the elementary-school level, but at the university level instead, and generalized to the lower grades. We cannot assume a kindergartener will undertake the process of engineering in the same way as a freshman in college, even if both are novices to the field.

Even including literature presented in Crismond and Adams' meta-analysis (2012), there are limited sources of data available that focus on elementary students engaging in engineering design practices. The few exceptions include studies focused on the following topics: problem framing (McCormick, 2015; Roth, 1995); drawing for planning (Johnsey, 1995; Portsmore, 2010; Rogers & Wallace, 2000); modeling (Penner, Giles, Lehrer, & Schauble, 1997); experimentation (Penner & Klahr, 1996; Silk & Schunn, 2008;); and journaling for metacognition (Wendell & Lee, 2010; Wendell, Wright, & Paugh, 2015). Katehi, Pearson, and Feder (2009) similarly note the lack of research at the elementary-school level, particularly in the younger grades (K-2), compared to the body of research for engineering education at the secondary and post-secondary levels. My colleagues at Tufts have begun to examine many of these practices with younger students. *Understanding the Challenge* or *Ask* metapractices were investigated by McCormick (Hynes & McCormick, 2012; McCormick & Watkins, 2015), who examined how fourth-grade students framed classroom engineering problems. The metapractices of *Represent Ideas* and *Plan* were studied by Portsmore (2010), through a study of how kindergarten and first-grade students use drawing for planning. Wendell (Wendell, 2011; Wendell & Lee, 2010) examined the *Weigh Options and Make Decisions* and *Create* practices through clinical interviews with third-grade students as they evaluated the properties of potential building materials for creating design solutions.

This dissertation covers unexplored territory within the field of engineering education in two ways. First, by investigating engineering practices specifically within the context of kindergarten and third-grade classrooms, my research will shed light on a neglected population of the youngest engineering education students. Secondly, I have chosen as the focus of this dissertation, and of my research project in general, the iterative nature of engineering design. Iteration is unequivocally inherent in the form of the engineering design process undertaken by professionals (Adams, 2001; Katehi et al., 2009), and yet is represented in engineering design process models or lists of engineering practices in varied, and often inadequate, ways. In traditional diagrams of the engineering design process (see Figure 1), iteration is listed both as a step (*Improve*), and is implied in the cyclical nature of the diagram itself. The *Matrix* (see Figure 3) includes it as *Revise/Iterate* in a list, alongside other essential engineering strategies employed by experienced designers.

As Cunningham and Carlsen (2014) point out, the NGSS omits iteration entirely from its list of practices (see Figure 2), perhaps due to the format of drawing parallels between the practices of science and engineering (Bybee, 2011;

Cunningham & Carlsen, 2014). In Appendix F of the NGSS, dedicated entirely to science and engineering practices, iteration is mentioned only once, and in the context of scientific modeling (National Research Council, 2013). Several of the standards at multiple grade-levels are dedicated to "revising" models, but if the NGSS intends to draw parallels between scientific modeling and constructing engineering design solutions, they document needs to be much more explicit. It is not inconsequential that scientific models do not serve the same purpose as engineering solutions; revision of scientific models bring representations created by people closer to fundamental truths about the universe, while revision of engineering designs produce functional and context specific solutions, striving toward meeting a goal through an optimal balance of trade-offs within a constrained system. As such, different practices must be used toward each end. Moreover, I could find no research at the elementary level addressing the topic of iteration within engineering design. Echoing the general critique of the NAE report (Katehi et al., 2009), iteration is essential to engineering design, and yet the field of K-12 engineering education has taken a haphazard approach to investigating it.

Background Literature on Iteration

Iteration is a goal-directed activity of making incremental refinements during the development of a design solution. Iteration is best conceived of as a metapractice, incorporating the practices of *testing* a design prototype to see if it meets the challenge specifications, *analyzing* the test results, and *proposing* solutions to any deficiencies. Thus, its representation by the *Matrix* a typical engineering design process representation as a singular strategy is unsuitable. A dependence on iteration to optimize solutions, along with the consideration of trade-offs and constraints, is one of the factors that distinguishes the practices of engineering design with scientific inquiry (Katehi et al., 2009). This is important in the context of STEM education for ensuring that science inquiry and engineering design are represented authentically as epistemologically related, but distinct, practices. Thus, its omission in the NGSS list of engineering practices is problematic. Engineering design lessons in K-12 settings often only allow time for a single iteration of a solution, and models of the engineering design process are sometimes depicted as being linear, or ending in iteration, rather than emphasizing revision throughout the process (Katehi et al., 2009), which does impact how teachers plan and enact engineering design challenges (McCormick, 2004). Thus, the placement of iteration as a step in a process, rather than as an overarching structure of the process, is curious; as a metapractice, iteration should not be placed on the same level as practices like planning, building, and testing. Therefore, to establish a background in this study, I eschewed K-12 models of engineering design, and instead looked toward the research on iteration in post-secondary and professional engineering.

Rather than a line or circle, experts' design processes typically take the form of a 'cascade' (Atman et al., 2007), where engineers combine problem structuring (*analysis*), problem solving (*synthesis*), and testing (*evaluation*) in managed, iterative cycles; however, many claim that novices tend to treat engineering design as either a regimented, sequential, and incremental process, or haphazardly revise without a clear goal (Adams, 2001; Crismond & Adams, 2012; Ennis & Gyeszly, 1991). In a series of analyses comparing professional engineers to university students, experts and college seniors were shown to cycle through design iterations more frequently than freshmen, and a greater number of iterative cycles positively correlated to the quality of the final design (Atman et al., 2007; Atman et al., 2005). If more frequent transitions between steps, more time spent on evaluation and decision steps, and willingness to revisit the conceptual design stage correlate to the quality of a final design (Atman, Chimka, Bursic, & Nachtmann, 1999; Devon & Dorricott, 1996), then opportunistic design decisions—which might not follow a neat, circular path—should be encouraged (Atman et al., 1999; L. J. Ball & Ormerod, 1995; Smith & Tjandra, 1998). Studies of university engineering students have also shown that iteration helps build a better conceptual understanding of the concepts behind their design (Adams, 2001). This lends to the idea that iterative design cycles should be encouraged as a motivator for higher order thinking skills for young students' design as well. While this has not been confirmed with young students, Levy (2013) has shown how children's conceptual understanding of physical systems can be embodied by the artifacts they construct; in her study, Levy was able to show how Kindergarten-aged students applied scientific concepts to problem solving that appeared to be well beyond their predictive ability. This feat was attributed to the reduced cognitive load of working with physical components, sensorimotor feedback, visual observations, and the opportunity to revisit solutions and tweak subsystems to change performance. This present study seeks to build upon these ideas in relation to the engineering design practices of elementary students, by also shedding light on unexamined ways teachers and classrooms can help their students iterate to achieve better solutions to design problems.

The charge Crismond and Adams (2012) make in the *Matrix* about *beginning designers*, which will be discussed in more detail in the following chapters, is that their patterns of iterations are either haphazard—working on the details to a solution at random—or linear—treating the engineering design process as a set of steps to be conducted, in order, once. But without citing any research at the elementary grades, their claim is unverified for these youngest students. From my classroom observations over the last six years, there is no question as to *whether* elementary students iterate; they do. I have observed (Kendall, 2015; Kendall & Portsmore, 2013; Wendell et al., 2014) students who would otherwise finish their work and ask, "What's next?" motivated to get a design solution working just right, or to add one more feature. I have seen students pick back up after their own failures, or critically examine other students' solutions to borrow from their successes. But this aspect of engineering design has never been thoroughly explored in the elementary classroom, and I seek to challenge *the Matrix's* view of beginning designers in two ways. One of my goals in this dissertation is to describe the form iteration takes in elementary students' activities while designing. The other goal, which is borne out in my theoretical framework discussed below, is to locate the many factors within the context of an elementary school classroom that contribute to the revision of elementary students' design solutions. Most of the studies cited in the *Matrix* derive their data from decontextualized clinical interviews and adopt a positivist research paradigm. In contrast, my dissertation is situated in the classroom, where the learning and practice of engineering design take place, and considers a more sociocultural view that encompasses as many aspects of the environment as possible that may influence a student's work.

Theoretical Framework

In order to complement the context-specific nature of my research, I employ an situative cognition framework to analyze my data. The situative perspective views "knowledge as distributed among people and their environments, including objects, artifacts, tools, books, and the communities of which they are a part" (Greeno, 1997, p. 97) and asserts that knowing is inseparable from doing, and learning is conceptualized as a meaningful participation in a community of practice (Barab, Barnett, Yamagata-Lynch, Squire, & Keating, 2002; Johri, Olds, & O'Connor, 2014). Greeno and Engström (2014) most recently use the term *situative* to refer in general to theoretical frameworks that follow from Vygotsky's (1978) cultural-historical approach to learning through social interaction and the use of culture-specific tools and signs; these frameworks include *activity theory* (Engeström, 1987), *situated learning* (Lave, 1988, 1993; Lave & Wenger, 1991), *situated action* (Suchman, 1985), *distributed cognition* (Clark & Chalmers, 2010; Hutchins, 1995), and *cultural psychology* (Cole, 1996; Rogoff, 2003). What all of these frameworks share is the perspective that it is impossible to separate action, cognition, and learning from the context in which it takes place, and thus all action, cognition, and learning, is situative (Johri et al., 2014). Johri, Olds, and O'Connor (2014) endorse the use of a situative perspective in engineering education research, largely due to its emphasis on context and engaging in practice. Roth and Lee (2007) show that activity theory is useful for both analyzing data recorded in real classrooms, and designing change within the classrooms when trouble and contradictions become evident in cultural settings. Nardi (1996) makes the argument that of these situative frameworks, activity theory provides the richest framework for studies of context in its comprehensiveness and engagement with difficult issues of consciousness, intentionality, and history[1]. For this reason, I chose to draw inspiration for my theoretical perspective most heavily from activity theory.

Nardi (1996) describes the essence of activity theory as, "we are what we do" (p. 43). Activity theory defines *practices* as regular and recurring patterns of activity, and labels people who participate in the same shared practices a *community of practice*; therefore, knowledge in activity theory is embodied by participating in a community of practice (Greeno & Engeström, 2014). For members of the community, learning can be considered the trajectory toward fuller and more meaningful participation in the community's practices (Lave & Wenger, 1991). Greeno et al. (1997) explain that the situative perspective of knowing and learning subsume behaviorist and cognitive perspectives, in that "rather than separating action from meaning, the situative perspective focuses on activities that communicate and construct meaning," (p. 117) and,

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[1] For a more extended analysis of issues in activity theory, see these sources, as well as the discussion within Chapter 2.

> rather than conceptualizing understanding of something as a private representation of it, constructed through transformations on mental symbols, understanding is viewed as the result of an activity that most typically involves people constructing common ground in conversations.... it involves an interaction of a person or people with symbolic material that has meaning through its function in communities that use it. (p. 117)

Additionally, they argue that situative views go beyond behaviorist or cognitive views of thinking to examine the development of practices of discourse and inquiry—and in the case of engineering design—processes that have been considered a means to an end, but in a situative view, are often the central goals of learning. The framework can also examine the finer-grained levels of *actions* (the concrete means through which activity is realized), and *operations* (the unconscious elements that realize actions) (Roth & Lee, 2007). An example offered by Nardi (1996) relates these concepts as follows: if a person takes a nature walk (*activity*) for the purposes of bird-watching (*object*, or goal), then they might lift their camera and push the shutter-release button (*operation*) in order to capture a picture of a rare bird (*action*).

Instead of examining cognition at the individual level, activity theory examines *activity systems,* groups of people at the dyad level or larger (Greeno & Engeström, 2014), such as the student groups found in elementary classrooms, named because they focus on "how people learn by engaging in activities, such as problem solving or making or designing something" (Greeno & Engeström, 2014, p. 1). Research on activity systems focuses on the ways in which the individual components act and interact with each other, and also focuses on larger contextualizing systems that provide *resources* (sometimes differentiated into *affordances* and *constraints*) for those actions and interactions (Barab et al., 2002; Greeno, 1997; Greeno & Engeström, 2014; Nardi, 1996; Roth & Lee, 2007). Activity theory is concerned with the socio-historical development of activity, and the mediating role of artifacts (Leont'ev, 1974, 1978; Vygotsky, 1978). Elements of an activity system can include the students, teacher, curriculum, educational materials and technology, classroom rules and culture, worksheets, etc. Analyzing the classroom context is not completed by simply identifying the people and artifacts involved, but rather in describing the transformative relationship between people and artifacts (Nardi, 1996). Activity systems are characterized by tensions between the components therein (Engeström, 1987, 1993; Leont'ev, 1974). Barab et al. (2002) explains that these tensions are critical to understanding both the motivation of a subject's actions, and also understanding the evolution of a system, as shifts in objective occur. Innovation and learning within the activity system are dependent on these tensions, and the interplay between components should be leveraged to drive the development of the system (Lave & Wenger, 1991).

Engeström (Engeström, 1993; Greeno & Engeström, 2014) has used the diagram in Figure 4, often called an *activity triangle diagram*, to help conceptualize the relationships between these various components of an activity system. In Engeström's (1987) framework for activity theory, the three major components (sometimes referred to as first-generation activity theory) are the *subject* (an individual or groups), an *object* (the goal of the activity), and the *mediating artifacts* (what Vygotsky would have called tools); the remaining vertices on the triangle (included in second- and third-generation activity theory) are comprised of additional social *resources* (including a community, its rules, and the division of labor). An *object* is not necessarily a literal thing, but might better be thought of as an objective, or motivation for the activity. As Engeström (1993) explains, "objects can be raw materials, conceptual understandings, or even problem spaces" (p. 67) at which activity is directed and which are transformed into outcomes with the help of mediating resources. Activity theory is concerned with describing what are the objects of the subjects' activities, and how they are related to the objects of other people, and to the resources and context of the system as a whole (Greeno & Engeström, 2014; Kaptelinin, 1996). In this dissertation, I have not employed the activity triangle diagram as a tool for analysis, but I feel it is a helpful visual representation of the interconnectivity of people, tools, and objectives within an activity system.

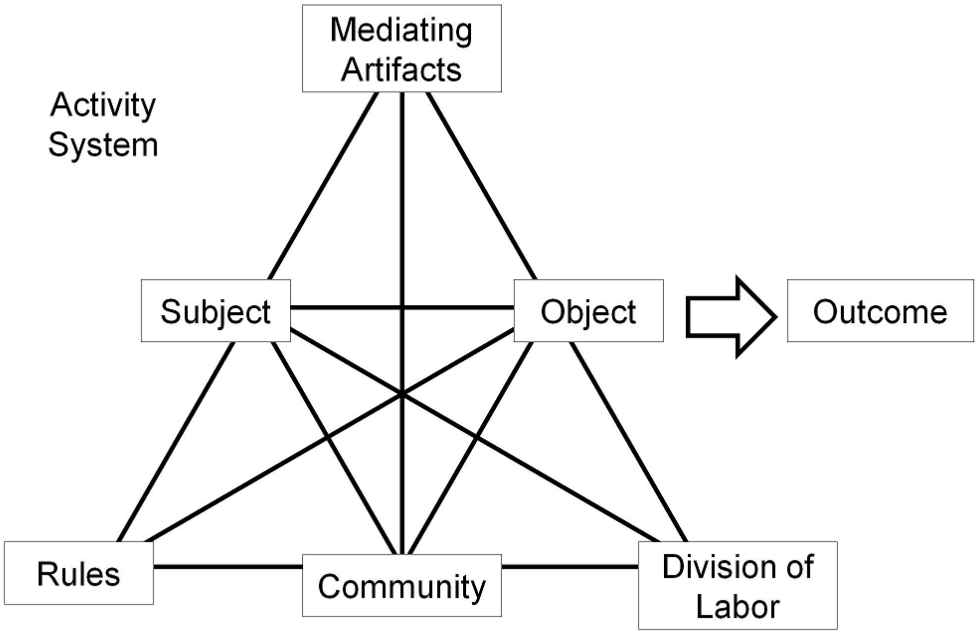

Figure 4. An activity triangle diagram, popularized by Engeström in order to represent the components of an activity system.

Activity theory is well-suited for application to research in engineering classrooms. Both activity theory and engineering involve practices that are goal-driven and rooted in communities. Activity theory focuses on the subject's actions relevant to some goal, or objective, and engineering design is purposeful, with designers utilizing practices to create a solution that meets a defined goal within a specific context. Greeno and Engeström (2014) describe the purpose of classroom instruction as students developing productive habits of mind in order to promote generative uses of domain knowledge, and support the idea that an important aspect of learning is a broadening of the subject's understanding of the objective. Engineers accomplish this as they gain knowledge about a solution and a system through background research, problem scoping, evaluation, and iteration (Crismond & Adams, 2012). Contradictions and tensions within the classroom, between subjects and the greater context, can bring about change and development in an activity system (Roth & Lee, 2007), just as the disparities between a design solution and the specifications must lead to revision of the solution. Barab et al. (2002), in their activity-theory analysis of a college astronomy classroom, claim that the transformation of an objective leads to scientific understanding that is mediated by tools and the overall classroom microclimate, such as the division of labor and community rules. Such transformation of objectives is congruous with the evolving nature of solutions and criteria within the iterative practice of engineering design.

Activity theory can be thought of not only as a theoretical lens, but also as an analytical tool that frames how we think about subjects and data collection (Barab et al., 2002). The unit of analysis for activity theory is larger than the individual person—either two or more people such as a dyad, a group, a classroom, a community, or an individual person working with objects and technological systems (Greeno & Engeström, 2014; Roth & Lee, 2007). Activity theory considers a subject's activity as mediated by various resources, and engineering is an activity mediated by not only physical artifacts but also social and collaborative aspects (International Technology Education Association, 2007; Katehi et al., 2009). In the classroom, resources can include interactions with other students and teachers, construction materials, books or the internet for gathering background information, worksheets and other aspects of the lesson plan itself, and the established rules of the classroom. Thus, when investigating the activity of engineering design, activity theory will help us break down the cyclical actions or practices which comprise the metapractice of iteration, and examine the resources mediating them. Relevant aspects of activity theory as they relate to methodology and data analysis are touched upon in greater detail in later chapters.

Research Questions and Dissertation Overview

Researchers (Greeno & Engeström, 2014; Kaptelinin, 1996) describe the fundamental question dictated by an activity theory analysis as, *what are the objects of the subjects' activities, and how are they related to the objects of other people, and to the resources and context as a whole*? Within classrooms specifically, Greeno et al. (1997) say the goals of activity theory are to analyze and understand how classroom activities, that occur with particular resources, are organized. Learning is framed as a change in the practices or objectives of an activity system (Greeno & Engeström, 2014), so attention should be paid to what encourages students to revise either their design solution itself, or their engineering design practices. In this dissertation, the topics for each of the three empirical chapters arose organically out of the context of the data, but each research question calls back to the fundamental question: *how do young elementary students engage in engineering design practices related to iteration as part of a classroom activity system?*

In this introduction, I have presented my case for studying how best to promote iteration in elementary-school classrooms, outlined my research goals and questions, and described my theoretical background.

In Chapter 2, I outline the larger research project of which this dissertation was a part, describe the participants of my research and the classroom context in greater detail, and explain my data collection, selection, and analysis methods.

In Chapter 3, I ask the question, *what constraints do students attend to when engaged in engineering design; and, how are shifts in attention to these constraints as students iterate upon their designs related to the resources and context of the classroom?* At the dyad-level in a kindergarten classroom, I present three cases through student dialogue and activity. Within each case, I examine the objectives of students attending to engineering constraints while engaged in the practices of iterative cycles of testing and revision. I argue that students attend not only to the *explicit constraints* (specifications) detailed in the initial challenge, but also the *emergent constraints*—defined by the students themselves, implicit in the materials chosen to represent the challenge during testing, or the context of the challenge presented through the lesson. As students iterate upon their solution, the activity systems in which they are working are in frequent flux, setting up and resolving tensions between the students' objectives and the resources within the classroom. These resources afford certain constraints over others, which influences the students' final designs.

In Chapter 4 I ask the question, *how do students' activities and objectives differ through plan-driven versus experimentation-driven approaches to iterative design?* I examine three cases at the group-level in a third-grade classroom, analyzing their dialogue and activity for the practices in which they engage, and their motivations for these practices. These cases feature students operating through the traditional top-down, planning-centered engineering design process, as well as a bottom-up, experimental-centered process (what some might call tinkering-based) is also utilized by some students. While the students engage in similar practices of reflection, testing, and revision, they execute these actions in differing patterns according to the objective of their activities. Additionally, I note how an experimental-driven approach provides affordances for students to build missing domain knowledge necessary for a functional solution.

In Chapter 5 I ask the question, *how do the four lesson criteria introduced in Chapter 2 influence the students' iterative activities of testing and revision?* I focus on cases of engineering design lessons in kindergarten and third-grade, documenting both dialogue and activity, but also artifacts and lesson plans. I describe the extent to which each lesson meets the four lesson criteria, and the effect of these criteria on solution evaluation and revision. I conclude that to promote iteration, students must have clear tests for subjective and objective specifications, and they must be able to anticipate what constitutes success for their solutions. Classroom affordances for promoting these productive engineering design behaviors are considered.

In the conclusion, I engage in a discussion of my findings, and consider how they are situated in the current literature, as well as how the practices I investigated—such as problem scoping, reflection, and testing—relate to both iteration and student learning. I suggest future avenues for research, and potential applications of this research for curriculum design and classroom practice.

Chapter 2. Research Context and Methodology

This dissertation takes the form of three empirical studies, each focused on a different aspect of the practices related to iterative engineering design. They are situated within the context of lessons featuring engineering design challenges, enacted in early-elementary classrooms. The data are presented as case studies, analyzed through, through the use of narrative summaries and illustrative examples, with a theoretical perspective influenced by situative cognition and activity theory. This chapter explains the rationale and implications of the study design, and details the data collection and analysis.

Study Design

Situative cognition asserts that sociocultural, mental, and material resources for action are intertwined (Kajamaa, 2012); context is at the crux of this perspective. As I mentioned in the Introduction, I choose to situate my dissertation research within the classroom—where the learning and practice of engineering design take place—and take a more ethnographic approach that encompasses documentation of as many aspects of the environment that may influence a student's work as possible. Within activity theory, context is not a wrapper or label one can apply to various situations; the activity itself is the context (Nardi, 1996). Thus, the context is also central to the object (or goals) of the subjects in the activity system.

In the workplace, as well as in the classroom, there are many characteristics of the problem space that may not be evident in the problem statement (how the problem is framed; resources available for research, experimentation, and construction; peer and teacher interactions, etc.) that lead to these problems being characterized as *ill-defined* (Jonassen, Strobel, & Lee, 2006). Therefore, context must be thoroughly analyzed along with student behavior in order to preserve the context in which the behavior took place and correctly identify the students' goals and the process of learning; particularly with students, are they designing for a "real-world" context, or a classroom context (McCormick & Watkins, 2015)? I do not feel these considerations have been addressed by the strategies for beginning designers described in the *Matrix* (Crismond & Adams, 2012). With regards to the importance of context, Nardi (1996) provides the example of three people on a nature walk.

> How do we account for variable responses to the same environment or "situation" without recourse to notions of object and consciousness? To take a very simple example, let us consider three individuals, each going on a nature walk. The first walker, a bird watcher, looks for birds. The second, an entomologist, studies insects as he walks, and the third, a meteorologist, gazes at the clouds. The walker will carry out specific actions, such as using binoculars, or turning over leaves, or looking skyward, depending on his or her interest. The "situation" is the same in each case; what differs is the subject's object. (Nardi, 1996, p. 42)

The situation is identical for all subjects, but their object (or goal) is different. Even if we observe the bird watcher and meteorologist engage in the same activity from a behavioral point of view, such as looking skyward or taking pictures, the intent, interest, and knowledge differs between the two subjects. Thus, descriptive and context-rich analysis methods, such as qualitative case studies, provide much necessary information for evaluating classroom learning through activity theory. The methodology and analysis for my study are heavily influenced by activity theory. The subjects of my data are student groups, rather than individuals. Activity systems eschew the study of individual cognition for the interconnection between the subject and the people and things in their environment; in my analysis, I attempt to include interactions with teachers, students, building materials, worksheets, and other classroom resources that provide affordances and constraints on student practice. This perspective also informs the way I define knowledge and look for evidence of learning. Because activity theory considers knowledge and learning to be tied to engaging in a practice, I will focus my observations and analysis on how students are engaged in the practices of engineering design within the classroom.

Greeno and Engeström (2014) describe three different ways in which activity systems can provide explanations for how learning happens:

> 1. An individual learns by participating in an activity system, and that individual's learning is explained by properties and processes within the activity system. One might call this a "top down" explanation, because learning of one component of the activity system—one participant—is explained by the activity system.
> 2. The activity system as a whole learns, and that learning is explained in terms of mental representations and behaviors of the

> participating individuals. This would be a "bottom up" explanation, sometimes referred to as a reductionist, individualist, or mechanist explanation. (p. 136)

I choose instead to take a middle road between the first two:

> 3. The activity system as a whole can be said to "learn"—when practices evolve, or interactional routines change, over time. A third type of explanation explains learning of the activity system in terms of properties and processes of the activity system. This would be a horizontal form of explanation, because the cause and effect are both at the same level of analysis. (p. 136)

This last approach has the benefit of noting a relationship between the activity system and the subject without inferring causation in either direction. In my analysis, I will look for evidence of learning by analyzing the subject's shifting activities and objectives as they engage with mediating resources. This attention to evolution is also congruent with my focus on the iterative practices of designing, evaluating, and re-designing in elementary classrooms. Specifically, I will accomplish this through examining how students test and what they test for, how they reflect upon the performance of their solution, and how they modify their solutions accordingly. Then I will discuss how these revisions demonstrate learning on the part of the subject.

Nardi (1996) explains that activity theory necessitates several conditions, including a research time frame long enough to understand not only the users' activities, but also their objective, including changes in objectives over time, where appropriate (Kuutti, 1991); attention to broad patterns of activity rather than narrow episodic fragments (which are useful for illustrating points, but not in isolation); the use of multiple data collection techniques, including but not limited to video recording, interviews, observations, and artifacts; and a commitment to understanding things from a subject, or "native" point of view. I have tried to meet these conditions by collecting data over the course of two lessons per classroom, enacted over several days. My video recordings capture not only the activities of three student groups in each classroom, but also the classroom at large. Throughout the lessons, in addition to the video recording, I took notes on my personal observations, interacted with students, asking them to explain their work or clarify an idea, and documented student and teacher artifacts through video and still photography. Reconciling the small-grained mediation between subjects and the classroom context, and the large-grained evolution of design solutions over the course of several hours of classroom time, was difficult to do in a concise manner. For this reason, I eschewed an analysis driven by activity system diagrams, and instead relied on identifying broader themes and tensions within the classroom transcripts, and presenting episodes demonstrating those themes as my evidence. More on my methods of analysis is detailed below, and in the methodology sections of Chapters 3, 4, and 5.

Research Context and Participants

The research in this dissertation took place within the context of a larger study aimed at introducing engineering design challenges into elementary classrooms. Over three years, twenty-three teachers in grades K-5 participated in professional development to create lessons that integrated engineering design challenges with the existing grade-level curricula. Major goals of this study included observing student and teacher classroom practices, evaluating the use of LEGO® materials for open-ended design, exploring optimal ways of building teacher pedagogy in engineering, and sustaining school-wide participation through professional development, teacher leaders, and grade-level cohorts. The program was a partnership between the elementary school, LEGO® Education, and the Tufts University Center for Engineering Education and Outreach (CEEO). In addition to professional development, teachers were provided with LEGO® materials for their classroom, and were paid a small stipend if they contributed lesson plans to a public, online repository.

The School

The participating school was a public, magnet elementary school with Title I status in a large, urban school district in the Southeastern United States. The school's demographics were representative of the state and district averages, with a 50% minority population (20.5% African American, 15% Hispanic, 10% Asian, and 5.1% two or more races) and a 30.9% free-and-reduced lunch population (National Center for Education Statistics, 2013-2014); however, with 68 different distinct ethnic groups, the school was the most diverse in the county. This particular school was already classified as a STEM school in its district, due to its offering of a Technology and Design "special" class—which students attended weekly on a rotation with music, art, gym, or library—and its partnership with higher education institutions and industries. Despite these existing attempts to establish engineering education in the culture of the school, the principal personally reached out to the CEEO to help train classroom teachers so that engineering could extend from the specials time into every aspect of the curriculum. Some teachers had previously implemented what they described as engineering design challenges in their classrooms as part of science lessons, or gained experience with LEGO® robotics kits during summer and extracurricular activities, but on the whole, teachers at the school were novices to engineering education. Therefore, students in the school had varying exposure to engineering depending on their grade-level and classroom teacher. During the 2013-2014 school year, when this research took place, 13 classrooms were participating in the program.

The Classrooms

The research was situated within one kindergarten (ages 5-6) and one third-grade (ages 8-9) classroom. The third-grade classroom consisted of students from two classes, typically combined for weekly, hour-long engineering lessons. I chose to focus this study on the early-elementary grades in order to explore this underrepresented area in the field of engineering education (Crismond & Adams, 2012). In order to ensure their reliable participation in this research, teachers were only considered for inclusion in the study if they had enacted at least one experimental lesson they had planned during the fall semester. Additionally, some teachers were located in small classrooms in temporary buildings, which made accommodating the necessary audiovisual equipment impossible, and so these classrooms were also not considered. After these qualifiers, I was left with three kindergarten classrooms, two first-grade classrooms, and five third-grade classrooms. I decided to focus on the oldest and youngest of these, presuming there would be little variance between the kindergarten and first-grade classrooms. From these remaining eight teachers, I asked for volunteers to participate in this research, which required enacting one additional lesson beyond what was required by the research program, and three teachers accepted.

The Teachers

Introductory demographic information was collected for all teacher participants in the larger study. Topics surveyed included educational background, years and grade levels taught, and questions assessing the experience and confidence with science and mathematics education and various educational technologies.

Ms. Cook[2], the kindergarten teacher, was in her fifth year of teaching, and had taught at several grade-levels spanning kindergarten to fifth grade. In her sophomore year of college, she had switched her major from secondary mathematics to elementary education because she realized a "passion for young students." This was Ms. Cook's first year in the research program, but she had already designed and enacted three engineering design lessons in her classroom from August through February. She reported that she felt very comfortable in teaching science and working with educational software, and she had previously participated in training for LEGO® products through the school, as well as having

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[2] All teacher and student names used in this dissertation are pseudonyms.

some personal childhood experience with the materials. I was not surprised to find such enthusiasm among these teachers, as previous research has shown that voluntary adopters of engineering curriculum amongst elementary teachers tend to have high self-efficacy scores with regards to science teaching outcome expectancies (Kendall & Wendell, 2012), meaning that these teachers were confident that their own effort in the classroom could improve student understanding of science content.

Ms. Bastille and Ms. Lyons, the third-grade teachers, had a history of team teaching by combining their classes for science or social studies lessons, and so their classrooms were analyzed as one. They were both in their eighth year of teaching, although teaching was Ms. Lyons' second career, and they were both in their second year of participation in the larger research program. Ms. Bastille had a bachelor’s degree in elementary education, and upon entering the program, she reported that she felt moderately comfortable teaching science and working with educational software, adding that she became "more motivated the more I know. I like teaching science." Ms. Lyons possessed a bachelor’s degree in economics, an MBA, and a master’s degree in education. She reported feeling very comfortable teaching science and working with educational software. Ms. Lyons was one of the few teachers who reported engaging in engineering in her classroom before entering the program, stating that her class spent about three hours a month on activities such as designing solutions to problems or redesigning a product. Ms. Lyons also served as the Science Olympiad coach for the school. Ms. Bastille reported approximately four years of experience using LEGO® products in her classroom (primarily SERIOUS PLAY®, a non-STEM-based product), while Ms. Lyons reported only one year of classroom LEGO® experience; this was in addition to personal experience these teachers had with LEGO® as children, or in playing with their own children.

During the first year of participation in the research program, teachers attended a three-day, intensive professional development workshop during the summer. Returning teachers attended the third day of the summer professional development in order to begin planning lessons for the fall semester, and all teachers engaged in a one-and-a-half-day workshop at the beginning of the spring semester. The professional development workshops focused on building teachers' pedagogical content knowledge (knowledge of how to teach a specific subject) for engineering (Hynes, 2012), as well as familiarizing them with the materials provided by LEGO®, including WeDo and Simple Machines kits. Using a learn-by-doing approach, teachers engaged in example lessons lead by researchers from the CEEO intended to showcase various ways of integrating engineering design challenges, LEGO® materials, and content standards. Lessons progressed in complexity through building from instruction booklets, to modifying existing artifacts to meet a challenge, designing solutions to instructor-defined problems, and finally guiding the participants themselves through defining the challenge specifications. Teachers were given blocks of time during each workshop to plan with their grade-level cohorts. Teachers were also required to attend monthly program meetings where additional lesson planning and documentation occurred. Time spent in the professional development workshops and monthly program meetings totaled 45 hours per year, in addition to discretionary time spent planning and preparing for lessons.

The Lessons

The teachers were already required to enact several engineering design lessons, of their own making, over the course of the school year. For this study, teachers were also asked to enact an additional engineering design lesson using craft and recycled materials, instead of LEGO® materials, so that the findings need not be material dependent. All lessons integrated content standards from the standard grade-level curriculum in mathematics, science, and literacy (see Table 1). Because the focus of my study is on the engineering design practices related to iteration, I assisted the teachers as they planned their lessons in order to ensure that the students would have the opportunity to engage in iterative design. To define the characteristics of lessons and classrooms likely to promote iteration, I surveyed my colleagues at the Tufts Center for Engineering Education and Outreach (CEEO), as well as the engineering education literature. The characteristics resulting from this survey are summarized below. In addition to co-planning the lessons with me, teachers were given a lesson-planning worksheet (see Appendix A) in order to articulate how their lessons would meet these criteria.

1. *The challenge is not over-constrained*. Authentic problems that expert engineers solve are ambiguous, ill-defined, and have multiple, divergent solutions (Jonassen, 1997; Katehi et al., 2009). Design, as such, is a formal, iterative search through a problem "space" for objects that satisfy multiple

constraints, or a journey from abstract to concrete or from ill-defined to well-defined (Adams, 2001; Hybs & Gero, 1992; Newell & Simon, 1972). In posing these kinds of problems to students, it ensures that students are not building from instructions, or that solutions are not predetermined for them. Allowing for varied solutions gives students a range of options to pursue, initially or after failure.

2. *The challenge has definable and non-subjective specifications*. Iteration is a "goal-oriented" process, so without a goal, there is no need for iteration or improvement (Adams, 2001; Hybs & Gero, 1992). Constraints that teachers can place on challenges in the form of specifications have the benefit of forcing students to confront trade-offs and engage in testing, the feedback from which should encourage iteration. These specifications should be non-subjective, or at least have a well-defined protocol for assessing success, otherwise students might be reluctant to be critical of their own solutions.
3. *Students are allowed a role in defining the problem*. Students could take a role in defining the challenge requirements, explaining how they know their solutions will meet the requirements, using the student as a client, etc. Authentic task environments are very much defined by human input, including personal cases, opinions, and perspectives (Jonassen, 1997). Studies have shown that a better understanding of the problem and more self-explanation improves the quality of design solutions (Adams, 2001; Devon & Dorricott, 1996; Sheppard & Jennison, 1997), and allowing students to help define the problem and specifications should result in a better understanding

of the problem. This will assist the students in effectively assessing their solutions with respect to the problem, and in re-designing for optimization.

4. *Testing and redesign are explicitly encouraged through the structure of the lesson and classroom.* Lessons should allow access to materials and freedom for testing at any time, not just at the end of the lesson, to allow students opportunity to reflect and revise. Research has shown that more frequent transitions between steps in the design process, and a willingness to revisit the conceptual design stage, correlates to quality of final design; opportunistic design decisions should thus be encouraged (Atman et al., 1999; L. J. Ball & Ormerod, 1995; Smith & Tjandra, 1998). Proficiency in problem solving is described as an ability to recognize dissatisfactory states and transform them into satisfactory states (Adams, 2001; Jonassen, 1997; Newell & Simon, 1972); in the absence of a "correct" solution for ill-defined engineering design problems, whether a solution is dissatisfactory or not can only be determined by how it performs in testing. A testing protocol can be modeled by the teacher or other students, but testing can also occur in smaller or less formal ways, and resources in the classroom can play into both.

Classroom	**Kindergarten**		**Third Grade**	
Lesson	Billy Goat Challenge	Garden Pest Challenge	Athletic Shoe Challenge	Marshmallow Thrower Challenge
Challenge	Build something long enough and strong enough for the three goats to cross the stream.	Build something to keep pests from entering the garden and eating your strawberries.	Choose a sport and design a shoe that meets the needs of that sport.	Design something, using a WeDo motor, to throw a marshmallow as far as possible.
Integrated Curriculum Topic	Mathematics: measurement of weight and length Literacy: The Three Billy Goats Gruff	Science: Basic needs of plants (water, food, sunlight) Literacy: The Tale of Peter Rabbit	Science: Human body physiology	Mathematics: measurement and charting data
Construction Materials	LEGO Simple Machines	Craft and recycled materials	Craft and recycled materials	LEGO WeDo
Lesson Duration	222 minutes over 3 days	114 minutes over 2 days	98 minutes over 3 days	116 minutes over 2 days

Table 1. An overview of the four lessons observed for this study.

The Billy Goat Challenge. This lesson was the first enacted in the kindergarten classroom. The challenge presented to the students was to build something long enough and strong enough for the three goats to cross the stream (two non-subjective specifications). The engineering design challenge was integrated with mathematics standards for measurement and comparison of weight and length, and also literacy standards through the folk-tale of the *Three Billy Goats Gruff*. With respect to the criteria that the lesson be "not over-constrained" and allow students a role in defining the problem, the objective was described as "something" to keep it open for the students to design something other than the traditional bridge from the story; however, all of the student groups eventually chose to build bridges. The building materials available to the students came from the LEGO® Simple Machines kit. At the classroom testing station, which was modeled for the students and accessible for the entire lesson, the stream the goats must cross was represented by two classroom chairs, with a 14-inch gap between them, and the goats were represented by rolls of pennies (one roll for the small goat, two for the medium goat, and four for the large goat). The lesson was enacted over three non-consecutive days, for a total of 222 minutes.

The Garden Pest Challenge. This lesson was the second enacted in the kindergarten classroom. The challenge presented to the students was to build "something" (solution not over-constrained) to keep pests from entering the garden and eating the strawberries, while still allowing sunlight and water to reach the plants (three non-subjective specifications). As the challenge was modeled after their classroom garden, students themselves played the role of client. The engineering design challenge was integrated with science standards for the basic needs of plants (food, water, sunlight), and also literacy standards through *The Tale of Peter Rabbit*. The building materials available to the students came from common craft and recycled materials, including straws, chopsticks, pipe cleaners, tape, cardboard, and paper. At the classroom testing station, the garden was represented by a small plastic basket filled with toy strawberries, the garden pests were represented by small toy rats, the sunlight was represented by a desk lamp, and the rain was represented by a spray bottle. The lesson was enacted over two consecutive days, for a total of 114 minutes.

The Athletic Shoe Challenge. This lesson was the first enacted in the third-grade classroom. The challenge presented to the students was to choose a sport and design a shoe that met the needs of that sport (giving students great latitude in their choices). The engineering design challenge was integrated with a science unit on the human body and physiology, and one member of the group was to wear the shoe. The day before beginning, the students watched a short documentary on how athletic shoes are designed and manufactured, and they discussed the structure and movement of the foot and ankle. The students were given an initial planning worksheet (see Appendix A) which asked them to identify the physical motions necessary to play their sport, and define the resultant properties the shoe would have to possess, with a few suggestions, such as "fast start" or "jumping up," and "flexible or stiff" or "bouncy or firm." There was also space for them to list the materials they planned to use, and a large sheet of paper to sketch their ideas. The building materials available to the students came from common craft and recycled materials, including cardboard, foam, fabric, ribbon, paper, and tape. There was no classroom testing station, but one student in each group was designated as the model for the shoe, and at the end of the lesson, the groups participated in a fashion show where they demonstrated their solutions. The lesson was enacted over three consecutive days, for a total of 98 minutes.

The Marshmallow Thrower Challenge. This lesson was the second enacted in the third-grade classroom. The challenge presented to the students was to build something, using a WeDo motor, to throw a marshmallow as far as possible: an extremely ill-defined (not over-constrained) problem with two very objective specifications. The lesson was integrated with mathematics standards for measurement and recording data. The challenge was presented as a contest with results recorded on a classroom chart, allowing students an engaging role in the problem and competitive motivation. Students were given an initial planning sheet (see Appendix A) which provided room for them to sketch a design, indicate how they would incorporate the motor, and brainstorm which pieces their design would require. For building materials, the students had unlimited pieces available from the LEGO® WeDo kits, including a motor and battery pack. At the classroom testing station, there was a starting line, feet marked on the floor, and a yard stick for measuring inches. The lesson was enacted over two consecutive days, for a total of 114 minutes.

The Students

Classroom sizes ranged from 21 students (Ms. Cook's kindergarten class) to 43 students (Ms. Bastille and Ms. Lyons' combined third-grade class). Students eligible to be included in this study must have had full parental consent and student assent to be videotaped in the classroom, to have written and constructed work collected or photographed, to be interviewed by the researcher outside of the classroom, and to have their videos shared for educational purposes. This stipulation left roughly two-thirds of eligible students in each classroom. Video recording these students with one camera would have provided a broad scope and required fewer audiovisual resources and less time to analyze. Some studies with similar designs (Hapgood, Magnusson, & Palincsar, 2004) have followed the teacher with a camera and microphone in order to sample thinking from all the students in the classroom. However, I did not wish to capture excerpts of student dialogue and work, but rather the entire arc of student thinking and practice, through successive iterative cycles. I was also conscious of not limiting the data to times when students were interacting with, or being overtly observed by, a teacher or researcher. Focusing instead on a few groups of students, and following those same students across both lessons provides a narrower scope, but a greater potential for rich data.

Students worked in dyads in the kindergarten classroom and in groups of three in the third-grade classroom. Given constraints on audiovisual resources and analysis time resources, three groups were chosen for observation in each class. Thus, study participants included six kindergarten students and nine third-grade students. These participants were chosen from eligible students using purposeful, maximum variation sampling, which is valid for qualitative research when trying to capture varying instances of a phenomenon (Glaser & Strauss, 1967; Honigmann, 1982) and ensured students were not clustered in any one of these parameters. Selection criteria included achieving equal representation of gender, race (white vs. non-white students), and academic achievement (high, middle, and low, as reported by teachers from beginning of the year assessments in reading and mathematics). Students were observed during a pilot lesson to confirm that their participation and discourse was suitable to be captured by the video cameras and microphones. Groups were formed from the 15 participating students at the discretion of the classroom teachers, as they had firsthand knowledge of the students' personalities and work habits (see Table 2 below).

Grade	**Group 1**	**Group 2**	**Group 3**
Kindergarten	Abed D'Andre	Christopher Simone	Paige Fatima
Third Grade	Cameron Jordan Kayla	Chantelle Sarah Thomas	Hannah Susan Jackson

Table 2. Student participants by grade-level and group. All names are pseudonyms.

Data Collection

Observations of lessons for student participant selection took place in March and the first research lessons were implemented at the end of that month, or in April. In May, all students were interviewed in groups, using an Evaluate-and-Redesign protocol modified from Crismond (1997, 2001); the results of these interviews are not part of this dissertation, but have been presented elsewhere (Kendall, 2015). The second research lessons were enacted in June, and data transcription and analysis began in July. See Figure 5 below for a timeline.

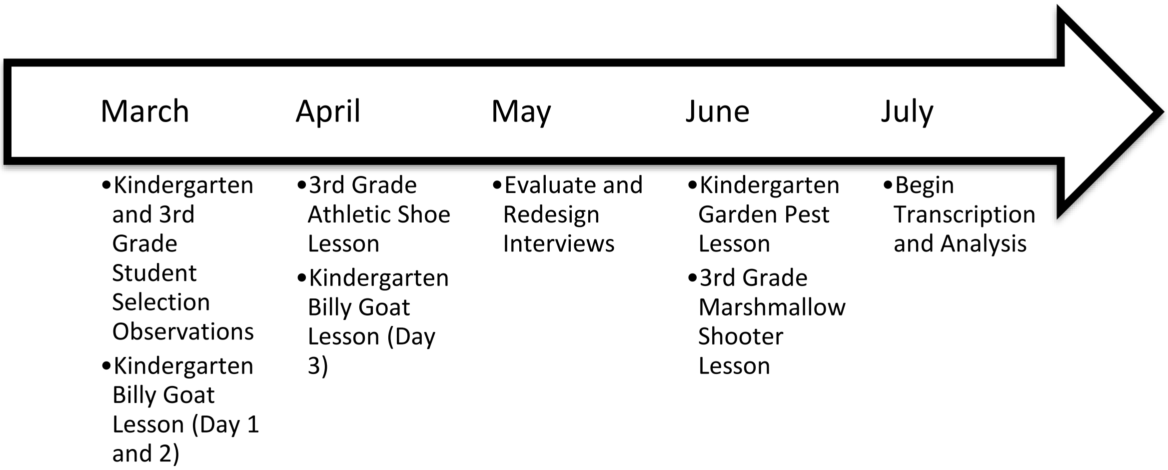

Figure 5. Timeline of Lesson Enactment and Data Collection.

Video data were collected through three video cameras with wireless microphones, one centered at each group's workspace. One additional camera was used to record any whole-class introduction or conclusion to the lessons presented by the teacher, as well as recording the events at the classroom testing station during the lesson itself. These videos were transcribed and annotated with the students' actions. Pictures of each groups' artifacts were taken at the end of each class period during the lesson, and any worksheets or planning papers from the participating students were collected. I was present for each day of filming, and in addition to operating the audiovisual equipment, assisted the teacher in facilitating the lessons, usually by circulating the classroom to ask students about their designs and answering general questions. In total, approximately 2000 minutes of video data were recorded and analyzed for this study.

Data Selection and Analysis

The research questions for Chapters 3, 4, and 5 emerged organically as I observed the classroom lessons and later transcribed the video data. My trajectory for analyzing the data can best be described by Merriam (2009), who writes:

> [T]he process is highly interactive. Your question takes you to some of the literature, which sends you back to looking anew at the phenomenon of interest. In trying to shape the problem, you go back again to the literature, and so on. In essence, you carry on a dialogue with previous studies and work in the area. (p. 50)

I initially intended to approach my analysis through grounded theory, a methodological paradigm in which the researcher reads and re-reads textual data, each time labeling variables within the data, and successively removes redundancies in the labels, as well as constructing categorical relationships between the variables (Glaser & Strauss, 1967; Strauss & Corbin, 1998). Echoes of this original analysis were retained in my preliminary processing of the data. For example, I transcribed the classroom videos and interviews, and then employed open coding, in order to identify themes within the data, paying particular attention to elements—such as student activities and objectives, or classroom resources and contexts—borrowed from activity theory.

The constant comparative analysis method (Glaser & Strauss, 1967) was also employed iteratively on successive passes through the transcripts, to re-analyze open-coded transcripts, in order to consolidate and refine the number of codes. Thereafter, this coding became less important for analysis, and more important for identifying episodes when the themes were salient in the classroom; I used the open-coding as a stepping stone in order to address my research questions through salient elements of activity theory (addressed in Chapter 1) in a narrative fashion. These case studies included illustrative examples from the transcripts, discussed below.

Data Analysis

Observational Case Studies. I have chosen to investigate my research questions through observational case-studies. Observational case studies are useful for presenting data from the complex, real-world context of a classroom (Merriam, 1998), and when answering *how* or *why* questions outside of a clinical setting (Yin, 1992). Studies of similar design include: Roth's (1995) ethnographic study with a situated theoretical framework of fourth and fifth-grade students engaged in problem scoping during an engineering design challenge; Smith and Tjandra's (1998) experimental observation of college seniors' iterative processes; and Wendell's (2011) case study of third-grade students engaged in engineering design employing a situative cognition framework and grounded theory analysis. Classrooms possess many natural boundaries (students, groups, lessons) that are well-suited for constructing cases (Merriam, 1998), and the two classrooms provided copious data about the students involved in each lesson, as well as data about the context and resources of the lesson (through classroom observations, artifacts, and lesson plans). Within this dissertation, I present three empirical chapters that each examine student activities in a classroom context through cases comprised of student groups working over the course of one lesson.

For each data chapter, the procedure for constructing cases was slightly different, depending on the research question. A more detailed account of the specific approach to data analysis is presented in Chapters 3, 4, and 5. However, there are several commonalities across the three chapters. Analysis always began with transcription of the classroom video for student and teacher discourse, and annotation for their actions and manipulation of the materials. This annotation was particularly important in the kindergarten classrooms, where students were prone to working silently without discussing their actions or intentions with their partner. Great care was taken to accurately portray non-verbal information (e.g. pieces being manipulated, student gaze, etc.) from those videos in order to present the best account of student work.

After transcribing, the data was open-coded and subject to constant-comparative analysis in order to identify themes within the lesson. From there, coding was used to parcel out the students' work into episodes (Barab et al., 2002; Derry et al., 2010; Nardi, 1996), which exhibited patterns of certain student practices within the lesson. For example, an episode within a case commonly captured one iterative cycle, from students identifying an aspect of their solution to work upon (analysis), to their work physically building or changing the solution (synthesis), to their assessment of the most recent modification (evaluation). Other episodes are more irregular, if this cycle was interrupted, or may show a singular activity, such as planning with the aid of a worksheet, or testing a solution at the testing station. All episodes were considered when constructing the cases, although not all episodes are represented in the final narrative summaries in each chapter.

Narrative Analysis. Narrative analysis is becoming an increasingly accepted paradigm within the engineering education research community (Case & Light, 2011). Derry et al. (2010) cite Bruner (1986) in explaining the logic of researchers using video to tell a story:

> Understanding is the outcome of organizing and contextualizing essentially contestable, incompletely verifiable positions in a disciplined way. One of our principal means for doing so is through narrative: by telling a story of what something is "about." (p. 90)

Through my role in the classroom—from advising the lesson plans, to assisting and observing the lesson enactment, to processing all of the resultant data—I was immersed in the experience of the teachers and students. While this does not give me an unbiased view—and ethnographic researchers would argue that an entirely unbiased view does not exist (Case & Light, 2011)—it does give me a comprehensive view of the context and outcomes within the classroom, from which I construct the "story." I have tried to maintain as analytical a perspective as possible.

My methodology is congruous with what Polkinghorne (1995) calls a "paradigmatic" approach, a relative of the constant-comparative analysis of grounded theory, where the researcher attempts to identify common themes across several narratives. In my case, these narratives describe themes within classroom lessons, with case studies of individual groups employed to provide evidence of these themes through exemplar episodes. These themes related to the practices and activities of students, the resources in the classroom activity system, and the tensions between activity system components. My epistemological framework is similar to Kajamaa's (2012), use of activity theory to provide analytical and conceptual tools for analyzing narrative accounts. In that research, Kajamaa advocates for using narrative inquiry as a form of organizational storytelling, as a tool for generating data, and in data analysis, explaining, "The concepts of object-oriented activity and material-artifact mediation, central in activity theory, are used as the core analytical concepts in this study" (Kajamaa, 2012, p. 79). These, along with investigations of systemic tension, are the elements of activity theory that I borrow most heavily in my analysis of the narratives.

Construction of Case Studies

In order to collate the various threads of narrative occurring at any one time in a lesson, I have organized them into cases centered around individual student groups. Each case is comprised of several components. Erickson (2006) argues that readers should come away from an analysis not only "tree-wise" but also "forest-wise" (p. 185); analysis cannot only rely on rich examples, but must also present the context of these examples within the larger corpus of data. I include narrative summaries (Derry et al., 2010) within a case to provide a sequential account of the larger-grained happenings within the classroom. Illustrative examples are chosen as fine-grained exemplars because they are interesting, relevant, and present themes in the most concise and digestible way, without having to pour through hours of transcripts (Barab et al., 2002; Derry et al., 2010). These illustrative examples are generally presented in narrative form with accompanying excerpts of the transcript and coding. The activity theory framework recommends the inclusion of some specific types of data; pictures of students at work, and classroom artifacts generated by the teacher and the students, are included in each chapter to demonstrate classroom resources mediating student activity.

In general, cases examine the activity of engineering design and the component actions (engineering practices) in which students engage, identifying the classroom resources providing affordances for these practices. In Chapter 3, I ask the question, *what constraints do students attend to when engaged in engineering design; and, how are shifts in attention to these constraints as* *students iterate upon their designs related to the resources and context of the classroom?* To answer this question, I coded the transcript for the constraints students attended to as they were talking, building, and testing, and then re-coded the transcripts to identify the resources relevant to specific constraints, episode by episode. In Chapter 4 I ask the question, *how do students' activities and objectives differ through plan-driven versus experimentation-driven approaches to iterative design?* For this chapter's analysis I focused on student activity, coding first for the fine-grained actions (including dialogue) and grouping these into larger cycles of activity based on the groups' objectives. This allowed me to compare the activities and objectives of groups that took different approaches to the design challenge. In Chapter 5, I ask the question, *how do the four lesson criteria introduced in Chapter 2 influence the students' iterative activities of testing and revision?* First I identified the two lessons not covered in Chapters 3 and 4 as being not as effective in promoting iteration based on the record of students' activity in the transcripts. Then, similar to Chapter 3, I identified practices, such as testing, and the classroom context and resources which played a role in these practices, pay special attention to shifts in student objectives as they iterate. More detail on the specifics of data selection and analysis can be found in each data chapter.

Chapter 3: The Role of Classroom Context and Resources in Student Attention to Design Constraints

> My favorite quick definition of what engineers do is "design under constraint." We design things to solve real problems, but not just any solution will do. (Wulf, 1998, p. 32)

Constraints in Classroom Engineering Design Challenges

According to the *Standards for Technological Literacy: Content for the Study of Technology* (International Technology Education Association, 2007), engineering design is purposeful, and the end-goal is shaped by *specifications* and *constraints*. *Constraints* are factors—such as costs, size requirements, and physical properties or quantity of materials—that place limitations on the design space, and *specifications* are a specific kind of constraint that define the parameters of what the engineer's design needs to accomplish. Not only functionality, but considerations of money, time, sustainability, aesthetics, creativity, ethics, and the social nature of meeting client needs are foremost in the minds of professional engineers (Jonassen et al., 2006). Furthermore, the iterative nature of engineering, the design and re-design of solutions, is governed by the specifications of the problem and the constraints imposed by the system itself.

In this chapter I investigate two research questions: To which constraints do students attend when engaged in engineering design; and, how are shifts in attention to these constraints, as students iterate upon their designs, related to the resources and context of the classroom? Classroom resources include, but are not limited to: physical materials, worksheets, stories and books, interactions between students, interactions with the teacher, and rules and classroom norms. These resources are the tools the subject uses in their efforts to transform the product of the activity according to their goal (Greeno & Engestrom, 2014). Student activity depends on, but is not singularly determined, by the available resources and community within which, and for which, the activity takes place (Roth & Lee, 2007). Using elements of activity theory, I examine both the *resources* providing *affordances* and *limitations*[3] on students' attention to constraints, and also how the students' *attention to constraints* shifts as they resolve systemic tensions within their activity systems and iterate upon their design. These topics lend themselves well to an activity theory perspective because this framework is primarily focused on the synergy between people and artifacts, as subjects participate in practices and work toward an objective, much like engineering design itself.

In classroom-based engineering design lessons, students are given challenges that are constrained to various degrees, from well-defined problems typical of traditional STEM curricula (Atman & Bursic, 1996; Jonassen, 1997), to ill-defined problems characteristic of professional engineering experiences (Jonassen et al., 2006). Coupled with the "real-world" constraints imposed by the design challenge (e.g., the needs of the user), engineering design lessons are additionally situated within a rich classroom context that includes practical or

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[3] The literature generally refers to resources as either *affordances* or *constraints*. I use the term *limitations* rather than constraints in order to avoid confusion with the engineering terminology.

social requirements beyond mere functionality (e.g., time limitations, working with partners, choice of materials). Also, Nardi (1996) explains that context is both internal to students, regarding their objectives and goals, and external, including classroom artifacts, teachers and peers, and community expectations. Furthermore, context is not static; from an activity theory perspective, context is a transformative relationship between people and artifacts engaged in an activity.

The interdependency and change inherent in an activity system is present in the student practice of attending to constraints as they work toward the goal of creating a successful design solution; for as the student works to iterate upon their design within the classroom context, the resources within this context (in the form of teachers, other students, materials, classroom norms, etc.) influence their understanding of, and attention to, the design constraints. Presumably, one way students develop agency and become fuller participants in the classroom practices of engineering design is through their attention to constraints. Students attend to constraints when they engage in activities such as problem scoping by identifying the constraints necessary for a design solution (analysis), planning (analysis) and building a solution to meet constraints (synthesis), and testing a solution to ensure that the constraints are satisfied (evaluation). These are essential practices comprising the iterative cycle of design (Katehi et al., 2009) (although there is room for others), and are examined in this chapter's cases. Below I will discuss what is known about how young students attend to design constraints, and more specifically how activity theory can help us describe the role of classroom context in their attention.

Student Thinking About Constraints

In their report *Engineering in K-12 Education* (Katehi et al., 2009), The National Academy of Engineering (NAE) cites a need for research that studies how K-12 students design with constraints in mind. The *Informed Design Teaching and Learning Matrix* (Crismond & Adams, 2012), aimed at K-16 engineering education researchers and practitioners, suggests that beginning designers become fixated on a solution—that they may not want to change or discard—and argue that beginning designers are not systematic in how they weigh or choose options when working within design constraints. Citing Dorst (2004), the *Matrix* also suggests beginning designers do not grasp how complex design problem-solving can be, or that problem parameters might be only partially defined at the beginning of a challenge. However, the "beginning designers" referenced in the *Matrix* are often college freshmen, who possess vastly different developmental and experiential profiles, and work within different classroom contexts than early-elementary students. Watkins, Spencer, and Hammer (2014) agree that studies tend to overlook the complexity found in experts' problem scoping, and argue for examining the ways students consider criteria while engaged in complex tasks beyond problem scoping. According to the *Benchmarks for Science Literacy* published by the American Association for the Advancement of Science (1993), the concepts of safety, time, cost, school policy, space, availability of materials, and other restrictions are appropriate to include as constraints on design for K-2 students. The NAE recommendations on K-12 engineering focus on the topic of engineering constraints through optimization and trade-offs (Katehi et al., 2009). Optimization—the manipulation of parameters in order to maximize the performance of a design—and trade-offs—in which a designer must make decisions about the improvement of one quality of a design over another—are important strands in the thread of engineering design education. However, optimizing a design is a complex process, and notoriously difficult for adults to navigate, let alone children (Katehi et al., 2009). I avoid this complexity by defining the scope of this chapter as student attention to constraints and the competing affordances and limitations of classroom resources, rather than trade-offs in the design solution.

Due to the lack of research on young children engaged in design, I find it helpful to compare a student's design solution to a scientific hypothesis; in engineering testing is used to evaluate whether a solution meets requirements, while in science testing shows whether a hypothesis fits data. In engineering design, some constraints are specified in the initial presentation of the problem, while others are defined by the designer in response to other factors in the design context, and constraints often interact with each other, resulting in trade-offs within the ultimate solution. In scientific inquiry, some variables are known (or at least suspected) to be causal from be beginning, while the existence and effects of others must be uncovered through experimentation, and variables often form complex mathematical relationships with each other. In this way, studies of how young students identify and investigate variables during scientific inquiry could inform our expectations for how they will attend to engineering constraints.

As early as kindergarten, students begin to develop the ability to choose evidence over theory when making predictions, and are able to recognize patterns of evidence across several scenarios (Ruffman, Perner, Olson, & Doherty, 1993). Kuhn (2007) suggests kindergarten students are able to identify variables during inquiry activities and hypothesize about their role in scientific systems, attending to variables based upon empirical evidence or prior knowledge and giving more weight to those they believe are salient to the phenomenon they are investigating. Ruffman et al. (1993) showed that kindergarten students also extrapolate evidence and hypotheses to make predictions about future data patterns. In relation to engineering design, these studies provide evidence that kindergartners might be able to identify pertinent constraints relevant to their design solutions, similar to how they identify variables within an inquiry activity, and also use evidence from testing to identify whether their design solutions are meeting the specifications of the challenge and predict the future performance of their designs, similar to making predictions about the behavior of a system based on their own hypotheses.

Constraints and Situative Cognition

Situating the students' work within an activity system, student attention to constraints can be examined as they work toward the objective of creating a successful design solution. The students' attention to constraints, as they engage in the iterative practices of planning, building, and testing, directly defines what success means for their solution, and is thus fundamental to their objective. Some resources for students in this lesson—the challenge posed to the students, the available materials, and the classroom set-up—were intentionally designed by the teacher and researcher to promote iteration through ill-defined problems, explicitly testable specifications, and readily available testing stations. Barab et al. (2002), in their application of activity theory to a university astronomy curriculum, describe the balance between teacher-directed instruction and student-centered learning. They advocate the role of the teacher espoused by constructionism (Papert, 1991), where the intent of the classroom environment is to support the emergence of activity systems that allow learners to extend their understanding; the risk is whether the planned resources are successful in encouraging students to attend to the desired constraints or not. The Billy Goat Lesson, for example, was meant to integrate mathematics standards on the measurement/comparison of weight and length, as well make the challenge difficult enough that a first attempt at a solution would end in failure, and the students would be required to iteratively improve it. In planning the lesson, the teacher and researcher chose to limit students' access to the longest LEGO® pieces in order to increase the difficulty of meeting the length requirement, and experimentally selected the materials for modeling the billy goats (rolls of pennies) in order to provide a weight which could physically cause LEGO® bridges to collapse. As teachers make these choices, they define much of the resources present in the students' activity system, setting up tensions for students as they design and redesign a solution within the system.

However, Barab et al. (2002) also point out that when teachers promote student-centered learning, they are seeding emergent activity systems in which students are free to develop their own constraints. Such affordances of the classroom context, through use of materials or interactions between students, may be unanticipated by the teacher and researcher as they designed the lesson plan, and therefore unassessed by the lesson's testing protocol. As Nardi (1996) says, "context cannot be reduced to an enumeration of people and artifacts; rather the specific transformative relationships between people and artifacts...is at the heart of any definition of context, or activity" (p. 38). The agency which students are afforded to engage in engineering practices within a lesson, including defining constraints, is a bellwether of students' role as full participants in the classroom engineering activity, and thus indicative of an understanding of problem scoping within an engineering design challenge, as well as ownership of the challenge. What resources, then, will students draw on to inform their attention to these constraints not planned for in the teachers' curriculum?

Through the framework of activity theory, this chapter not only characterizes the constraints to which students attend as they design, test, and redesign their solutions, but also examines the role of resources within the classroom context in informing the students' iteration upon their design solution. Within three case studies, I argue that the context of the lesson provided certain affordances that influenced how young students attended to not only the *explicit constraints* defined as specifications by the engineering design challenge, but also the *emergent constraints* derived by the students from the ill-defined context of the challenge itself. Tensions between the students' solutions and resources in the classroom—particularly the testing station and protocol—played a large role in shaping those solutions through iteration, while systems lacking that tension showed less influence on the final design. The students' attention to *explicit constraints* suggests their successful adoption of the specifications set forth by the teachers in engineering design challenge, while their attention to *emergent constraints* shows an agency acquired through participation in the engineering activity, in the context of the classroom and the challenge itself.

Methodology

Study Design

I approached my research through observation of three kindergarten dyads as they designed solutions to an engineering design challenge: build something with LEGO® materials that is long and strong enough to help three billy goats cross a stream. The challenge was designed to integrate with literature (through the folk tale of the *Three Billy Goats Gruff*), and also with a mathematics unit on measurement (weight and length). As such, the teacher and I chose the challenge statement, specifications, and materials for the challenge to ensure that students explored the dimensions of *weight* and *length*, and also required them to make very efficient use of their materials. We deliberately, and through experimentation, selected the distance between the chairs, weight of the goats, and choice of building materials available (see Figure 6) such that students would be likely to fail the first time and would be forced to iterate. This is on the recommendation of previously established literature suggesting that iteration leads to better learning outcomes and better quality solutions (Atman et al., 2007; Atman et al., 2005). During the lesson, the teacher was present at the testing station to scaffold testing by guiding students through the protocol and use of testing materials, which involved first assessing the length of the solution relative to the chairs, and then setting each goat in turn (from lightest to heaviest) at the beginning, middle, and end of the solution to assess its strength.

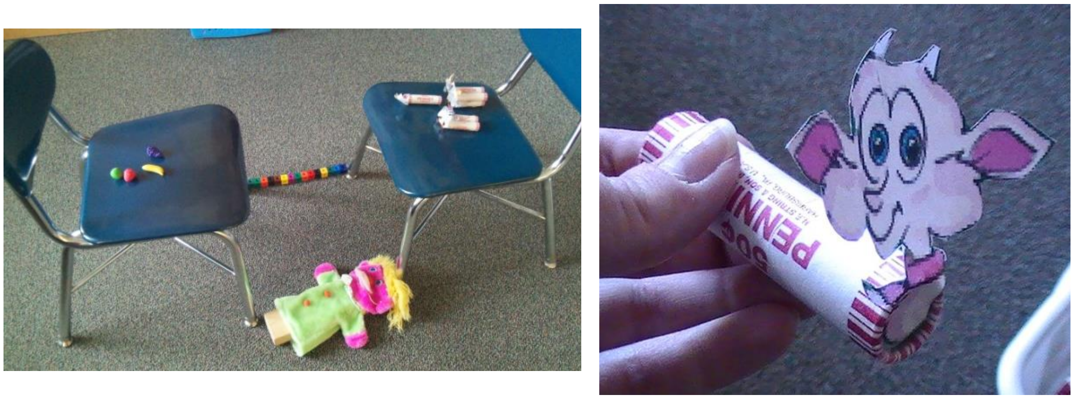


Figure 6.The classroom testing set-up. Left, the chairs representing the banks of the river the goats must cross. Right, the smallest billy goat, made from one roll of pennies. The medium and large billy goats were created from two and four rolls of pennies, respectively.

Participants

The research was situated within a kindergarten classroom (ages 5-6) of 21 students, with a lead teacher, teacher assistant, and student teacher. Ms. Cook, the classroom teacher, was in her first year of participating in the engineering education initiative at this school, but was enthusiastic and confident about enacting engineering curricula. Within this classroom, I chose to follow three dyads throughout the course of the entire challenge because I determined that this would provide me with more depth of understanding than capturing fragments of each student in the class, and would allow me to observe the students both in the presence and in the absence of the teacher or other adults. Those three dyads featured in this chapter are Christopher and Simone, Abed and D'Andre, and Fatima and Paige (see Figure 7). With advisement from Ms. Cook, these students were chosen to provide a maximum variation sample of ethnicity, gender, and academic ability. Dyads were formed at the teacher's discretion. Christopher and Simone often constructed solutions in parallel, and attempted to combine them for a finished product with mixed results. These two were playful while building, and chatted together about topics not related to the challenge. Abed and D'Andre had a different relationship; while Abed took the lead and was the "big ideas" person, D'Andre was quiet and thoughtful, and often found ways to implement Abed's plans and ensure their solution was on track. Similarly, Paige took the lead in the third dyad, while Fatima remained engaged through playfulness and helpfulness.

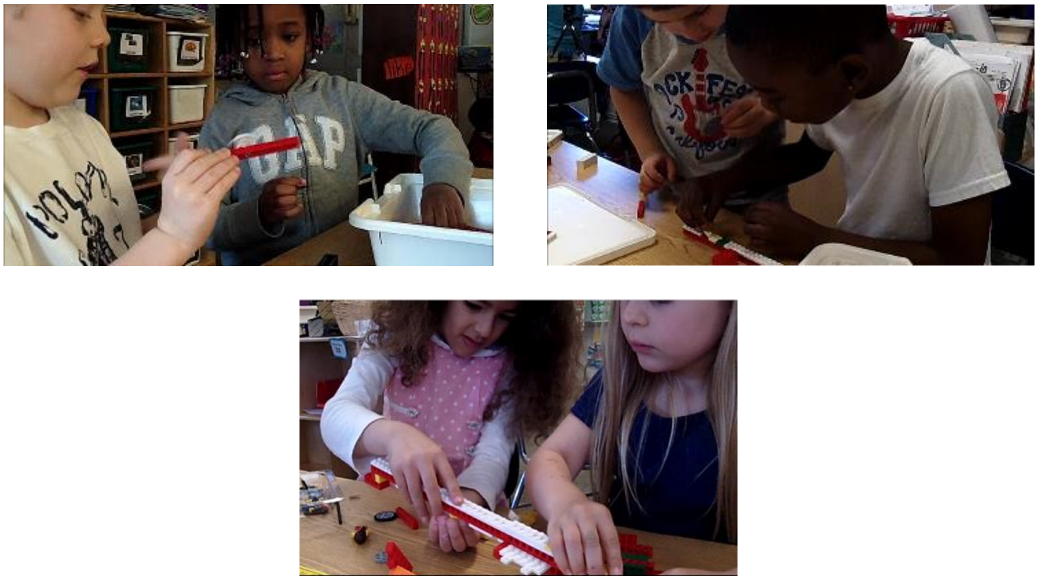


Figure 7.The three dyads in this chapter's analysis. Christopher and Simone (top left), Abed and D'Andre (top right), and Fatima and Paige (bottom).

Data Collection

Data were collected in several forms, through notes from direct observation of students within the classroom, photos of artifacts in the classroom, video recordings with a small camera and external microphone at each dyad's desk (three total), and a fourth camera capturing whole-class discussions at the beginning and end of each lesson and otherwise directed at the classroom testing station. These sources were chosen to gather evidence of dialogue between students, or students and teachers, and artifacts created, referenced, and used by the students and teachers. The video recordings were essential in capturing the students' actions and manipulations of the materials, which were as crucial to the study as dialogue, because much of their time was spent silently exploring the materials. These kindergarten students were not exceedingly verbal with their partners while building, and they did not act as collaboratively as students in older grades. Much of the students' intent had to be extracted from non-verbal discourse, such as the specific LEGO® pieces they chose from the available materials, their attempts to incorporate these pieces into their solution, and other general interactions with their solutions, such as dropping or bending them to test their durability. Through this data, I assembled a holistic view of the classroom activity systems, including student interactions with people and artifacts, division of labor, and community rules and practices.

Data Selection and Analysis

I began my analysis by transcribing the videos, including dialogue and annotations for the students' non-verbal actions and manipulation of the materials. My first research question was to identify which constraints students attended to. In the first pass, I accomplished this by utilizing an open coding method to note what constraints students were attending to and when, being sure to include the challenge specifications of *length* and *strength* as *a priori* codes. I engaged in a second-pass coding using the constant comparative method (Glaser & Strauss, 1967), where I was able to consolidate my first-pass codes into six categories of constraints (see **Error! Reference source not found.** below). These six c ategories, which included both the *a priori* codes and *inductive* codes generated during the first-pass, were further categorized as either an *explicit constraint* (explicit in the specification of the challenge) or *emergent constraint* (student-derived from the lesson context). This established the constraints to which students attended during the lesson. To identify the mediating factors relevant to the students' attention to each constraint as they iterated upon their solutions, my second research question, I open-coded the transcripts a second time with information about the resource(s) from the classroom (specific materials, interactions with teachers and students, the testing station, the story, testing protocol, etc.). From this I could identify the mediating factors that afforded and limited attention to specific constraints within the narratives included in my analysis. This allowed me to generalize patterns I observed in how classroom resources facilitated the evolution of students' designs.

Explicit Constraints		**Emergent Constraints**	
Constraints introduced in the challenge statement:	*Length* *Strength*	Alternative constraints to meet the explicit constraints:	*Weight* *Motion*
		Constraints introduced by practical considerations of the construction and testing materials:	*Balance*
		Constraint introduced by the context of the challenge, and needs of the users:	*Story*

Table 3. Constraints attended to by students while designing and building their solutions,

identified through *a priori* and inductive coding.

I assembled case studies for each dyad to establish how student attention to constraints evolved over the course of the lesson. This provided three narratives to establish a relationship between the classroom context (and all its varied resources), a shift in the objective of the activity system (the student attention to constraints), and the iteration of the final product (the design solution itself). For each case presented below, I have used Barab et al.'s (2002) methodology of isolating snapshots of actions (or sequences of actions) and framing them in terms of the constraints considered and the mediating resources. "Illustrative examples" are used as "grounded instances of course activity" (Barab, 2002, p. 86), in the form of transcripts.

Findings

Explicit and Emergent Constraints

As shown in Table 3, students considered two classes of constraints: *explicit* and *emergent.* The *explicit constraints* were those delivered by the teacher through the stated objective of the engineering design challenge. *Emergent constraints* were those that surfaced as requirements for the design solution based on implicit factors in the context of the lesson itself, such as the provided materials, the testing station, the interactions between teachers and students, and the end-users of the solution. These resources in the classroom, along with the planned lesson itself, provided tension within the activity system as students considered not only the *emergent constraints* in their objective, but the *explicit* ones as well.

Exploring these contextual differences between the *explicit* and *emergent constraints* to which students attended requires zooming in closer on the system and considering the underlying context surrounding each constraint. Simply classifying constraints into these two categories, of course, neglects the change in the students' objectives, and the revisions to their design solutions that occur across the course of the lesson. In the second section, a more dynamic view will be discussed where the instances at which students shift focus and begin to attend to new constraints, and the resources influencing them, are examined closer with the aid of activity theory.

Constraints Considered by Students

Explicit Constraints. During this engineering design lesson, the students were given two *explicit constraints* in the original challenge statement: their solution had to be *long* enough to reach across the stream and *strong* enough to hold each of the three billy goats. Most directly, resources affording the constraints of *length* and *strength* came as the teacher, Ms. Cook, repeatedly reinforced the challenge statement during whole-class discussions, through scaffolding at the testing station, and in individual discussions with students. At the testing station, the testing protocols and testing materials were specifically chosen to assess the bridges' *length* and *strength*: by spanning a set distance between two classroom chairs, and by holding three billy-goats made from rolls of pennies. Partners often reminded each other of the challenge specifications while they were building or testing. And the materials from which the students could construct their bridges, in this case the LEGO® Simple Machine set, offered in affordances for attending to *length* or *strength*. For example, depending on the method of connecting the LEGO® pieces, the construction could be very weak, or nearly impossible to break. Or, the longest beams in the kit would have made meeting the *length* requirement simple, had there not been a limited number of these pieces in each kit, and thus the materials provided the opportunity for students to think more critically about how to meet this requirement, and also increased the likelihood that more than one iterative cycle would be necessary to be successful.

Emergent Constraints. Students also attended to constraints beyond those explicitly addressed in the challenge statement. *Emergent constraints*, or those constraints that are implicitly born out of the context of the classroom and the engineering design challenge, must be identified by students themselves rather than defined for them. Some *emergent constraints* were directly related to the specifications from the challenge statement. For example, many of the students' earliest ideas included building vehicles—such as planes, boats, and cars—to employ *motion* to carry the goats across the stream, rather than constructing something that met the *length* constraint. Students contemplated not only the weight of the goats, but also the *weight* of the bridge itself, sometimes favoring lightweight designs, and at other times conflating heaviness with *strength* when trying to meet that specification. That the solution be heavy or light (*weight*), or that it be able to transport the goats (*motion*), were not specifications explicitly imposed by the challenge statement, but rather substituted by the students in order to meet the charge that the solution be "*long* enough and *strong* enough" for the goats to cross.

Other *emergent constraints* identified by students were implicit in the context of the classroom—from decisions made by the teacher when planning the lesson, such as the choice of building materials, or how the goats and stream were represented at the testing station. For instance, students' bridges that technically met the *length* constraint were not necessarily successful in spanning the gap at the testing station; the constraint of *balance* was necessarily introduced due to the smooth, curved top of the chairs representing the banks of the stream. Another *balance* consideration implicit in the choice of testing materials involved the round, wide goats rolling off bridges which were too narrow. Rolls of pennies were chosen to model the goats at the testing station because their weight was sufficient to break a LEGO® construction while still being compact enough to easily sit on one, and neither of these potential instabilities were anticipated by the teacher and researcher as constraints prior to lesson enactment. *Emergent constraints* drew not only from the challenge's materials and testing protocol, but also the context of the *story* of the *Three Billy Goats Gruff*, and the needs of the goats as clients or users. Some constraints derived from the *story* included methods for defending the goats against the troll, such as making the bridge higher, or improving goat usability by adding stairs.

Shifts in Attention to Constraints During Iteration

In the cases that follow, I will explore the students' interactions with the resources in the classroom and in the lesson, and the relationships between these resources and their attention to constraints within their design solutions. I will also examine the shifts in attention, from one constraint to another, as they engage in the process of iteratively re-designing their solution throughout the lesson.

Case 1: Abed and D'Andre. From the very beginning of the first day, Abed and D'Andre focused on the *explicit constraints* given in the challenge. In fact, Abed prototyped two designs at his desk, testing how they met the constraints of *length* and *strength*, before pursuing a bridge solution (see Chapter 4 for more detail about Abed's prototyping). His prototype bridge design was not long enough, and he was limited by the number of long beams to extend the solution, so he and D'Andre rebuilt the bridge with two rows of long beams, and plates covering the top to reinforce the seams between beams and provide a surface for the goats to stand upon (see Figure 8). This would be the basic design upon which they would revise iteratively for the remainder of the three-day lesson. By the end of the first day, Abed and D'Andre were ready to assess the *length* and *strength* of this bridge at the classroom testing station, scaffolded by Ms. Cook. *Length* proved to be an easy constraint for the boys to evaluate, and upon setting their bridge between the chairs they identified that it was too short. With the remaining time left in the class period, they returned to their desks to extend the bridge using the same construction technique as before, and prepared to test again on the next day.

Figure 8. Abed and D'Andre's bridge at the end of the first day. The structure of the bridge consisted of two rows of long beams, topped by plates which served the purpose of holding the bridge together and making the seams between beams stronger so that length could be added.

Up until this point, Abed and D'Andre had attended almost exclusively to the *explicit constraints* of *length* and *strength*. At the testing station, the students were exposed to new classroom resources beyond the testing materials, including the influence of the teacher and the rules of the activity (in the form of the testing protocol). These resources also generally focused on the *explicit constraints*, as the testing materials and protocol had been designed to assess the specifications put forth in the challenge statement. The nature of the testing protocol prompted the students to think about *length* first and *strength* second; a bridge could not be tested against the weight of the billy goats if it would not yet sit across the gap between the chairs. The teacher's actions focused on guiding students through the testing protocol and helping them to articulate their observations and next steps.

Resuming their testing on the second day, D'Andre recognized that although their bridge technically reached from one chair to the other, it still slipped off the chairs (see Figure 9, lines 1-9). This was the first opportunity for Abed and D'Andre to consider another factor, *balance*, implicit in the way the goats and stream were represented at the testing station; students would have to take into account the classroom chairs' smooth, rounded edges when ensuring their designs would sit independently across the gap. I identify *balance* as a separate constraint from *length* for two reasons: 1) D'Andre's solution to the instability is to make it longer, but the problem of *balance* could also be solved by other means, such as widening the ends of the bridge that sit on the chair to make them more stable; and 2) the bridge slipping off the ends of the chairs was just one example of instability, which also included bridges that flip over, or allow the penny-roll goats to roll off of them.

1	D'Andre:	It needs to be a little bit longer.	The constraint *balance* is afforded by the testing materials, and the teacher's scaffolding of the testing protocol.
	Teacher:	Did you hear that Abed? Now, why do you think that, though?	
	D'Andre:	[Pointing to the chairs.] Because it has to go from this chair to this chair.	
5	Teacher:	And so right now, is it able to go from one side of the stream to the other?	
	D'Andre:	Yes.	
	Teacher:	A little bit, but D'Andre's saying that maybe we can make it longer, right? Because it keeps doing what?	
10	D'Andre:	Falling.	
	Teacher:	Falling. So, why don't you guys go back and work on that, ok?	

Teacher:	D'Andre, what's happening here?	D'Andre is attending to the *balance* constraint (via *length*) afforded by resources at the testing station, while Abed focuses on the *strength* of the bridge, afforded by his experiences building.
D'Andre:	We need to make it even longer.	
Abed:	And we need to have something that holds it [he is adding axles through the holes in the beams].	
Teacher:	That holds it together?	
Abed:	Yeah.	
D'Andre:	Yeah, so it doesn't fall apart.	
Abed:	So it doesn't break apart anymore, while we're building.	

Teacher:	[The bridge no longer slips off the chairs.] Ok, so tell me what you see, before I even put the billy goat up there. What do you see?	The testing materials and protocol, and the teacher's scaffolding, afford Abed and D'Andre's prediction that the bridge is not strong enough in the middle to hold a goat.
Abed:	Not [strong] in the middle, it's bending.	
Teacher:	Where is it bending?	
D'Andre:	The bottom [he points to the bottom side of the bridge, in the middle].	
Teacher:	The bottom. So, it's already bending and the billy goat's not up there. Do you think if I put the billy goat up there that it will stay together? Or do you think it will fall apart?	
D'Andre:	Fall apart.	
Teacher:	So, what do you think, because where is it bending?	
Abed:	Down.	
Teacher:	On the bottom? Do you think that you would be able to make any changes, or do you think this is as good as your bridge is going to get?	
Abed:	Change it.	

		
Abed:	We need to turn [the bridge] over. We need flat pieces. [They add flat plates on the bottom of the bridge to reinforce the seams.]	Using building materials, Abed and D'Andre attend to problems with the *strength* of the bridge identified at the testing station.

Figure 9. Abed and D'Andre test and revise their bridge, attending to problems with constraints identified at the testing station.

When the boys returned to their desk, the assistant teacher approached and asked them what they were working on, D'Andre repeated his analysis from the testing station, the need to make the bridge "even *longer*" (Figure 9, lines 13, 18). Abed's attention, however, had shifted to the *strength* of the bridge, adding that they needed something to hold the bridge together so it did not break (lines 14-15) and proposing the addition of axles through the holes of the beams, perpendicular to the deck of the bridge. While both students attended to *explicit constraints* introduced in the challenge statement, D'Andre continued to attend to the constraint of *length* (via the need for *balance*), informed by his experience at the testing station, while Abed instead switched his attention to the *strength* of their bridge, presumably inspired by the challenge statement, and bolstered by the building materials he was proposing they use. Their differing goals were not at odds with each other, as they were able to incorporate both of their ideas for improvement within this iteration of their design.

Their subsequent return to the classroom testing station informed both of their goals, and provided evidence that while the bridge now met the *length* specification and *balanced* between the chairs, the bridge was bending in the middle under its own weight with no additional load (see Figure 9, line 22). Ms. Cook asked the boys to predict what would happen if they put the smallest billy goat on, and if they wanted to change their design before testing the *strength* of the bridge, which they did. Based on their interactions with the teacher, the testing protocol and testing station materials, the boys predicted that their bridge would not hold the billy goats, and also identified the weak spot in their design. Although Abed's addition of axles was an attempt to reinforce the bridge's *strength*, their trial at the testing station showed that the axles were not effective (or at least not effective enough). As soon as they reached their desk, Abed was quick to propose a revision to their solution specifically to address this observed weakness, by adding plates for support along the bottom to reinforce the seams there, and to keep the bridge from bending (lines 36-37). This iteration of the bridge proved to be their most successful, allowing the small and medium billy goats to cross before breaking.

Throughout multiple iterations, Abed and D'Andre attended mostly to the specifications of *length* and *strength*; while they may have been responding to other classroom resources, such as the building materials, their steadfast attention these *explicit constraints* demonstrates the influence of the challenge statement presented at the beginning of the lesson. The boys frequently visited the testing station, which was intended by the teacher to provide affordances for thinking about and meeting constraints of *length* and *strength*, including as resources the testing materials, the testing protocol, and scaffolding from the teacher. While the boys primarily attended to the *explicit constraints* in their testing, attention was also briefly placed on the *emergent constraint* of *balance*, in response to the unstable nature of their bridge on the classroom chairs of the testing station. They did not consider *emergent constraints* derived from the context of the *story* of the *Three Billy Goats Gruff*, which would not be afforded by either challenge statement or the testing station. Within this case's activity system, the testing station provided the tension which forced them to iterate upon their solution multiple times, and reinforced their attention to *explicit constraints*. Tension between their design and the testing station informs their design choices when revising, such as when D'Andre addresses the constraint of *balance* by extending the bridge using the same successful building technique he had used in an earlier iteration to meet the *length* specification, or when Abed implemented a way to strengthen their bridge at the weak spots explicitly identified in their analysis at the testing station.

Case 2: Christopher and Simone. Early on the first day, half of the class had chosen designs where the *strength* and *length* specification were not going to be testable given the testing station's materials (the chairs and penny-roll goats) and testing protocol; with diverse solutions such as cars and boats, the *length* specification had been replaced by the *motion* constraint, and rendering the *strength* specification irrelevant. Christopher and Simone, for example, began the challenge by planning an airplane to carry the goats across the stream (referred to below, Figure 10, lines 9-11), where the *motion* of the airplane would be provided by their own hands. In order to maintain the connections to the measurement content from the mathematics curriculum and the materials at the testing station, Ms. Cook further defined the challenge, with a classroom announcement adding that the students' designs had to be something the penny-roll goats could use on their own; thus, students were not allowed to carry the goats across the gap via their own hands.

1	Teacher:	That's great. Let's see if it works.	The testing protocol and materials afford Christopher's observation that their bridge still does not meet the *length* constraint.
	Christopher:	They [the chairs] need to be closer together.	
	Teacher:	What do you mean, it needs to be closer?	
	Christopher:	See how it is? It [the bridge] isn't big enough to go on it. That's	
5		what I'm talking about.	
	Teacher:	Oh, well then what are you going to do to fix that?	
	Christopher:	So, we're going to put it more. How about one more of these [staircases], Simone?	

Simone:	Christopher, didn't we say we were going to build an airplane?	Simone references their original airplane design, but Christopher points out the limitations of the goats as users.
Christopher:	Yeah, but the goats couldn't get into the airplane. So look what I created. [Adds pieces to one end of the bridge.]	
Simone:	Do we need any of these gears?	
Christopher:	No, we don't. Now probably we can do it. [Gets up to test if bridge is long enough, but the bridge breaks before they can test.]	
Teacher:	Alright, Simone and Christopher, you need to be getting your pieces. Go back with your partner and get your pieces together.	Christopher and Simone struggle with the limitations of the building materials as they keep the bridge *strong* while increasing its *length*.
Christopher:	[Takes stairs off and adds them back.] Our bridge! Look at it now, Simone! We're going to win this before anyone else can do it.	

Simone:	Let's go test it now.	Simone introduces sprinkles, a user constraint afforded by the availability of the building materials.
Christopher:	But a group is there.	
Simone:	Let's put more [pieces on].	
Christopher:	But we don't need this. That's not going to help. [He takes the stairs off again.] But you know what we could do?	
Simone:	You can get all these little pieces and sprinkle them on the bridge.	
Christopher:	Whoa, that's how you make a cupcake.	
Teacher:	How is that going to help the goat get across?	Simone identifies another affordance for the sprinkles, from the story (staying quiet).
Simone:	It could be so quiet so it [the troll] could sleep.	
Christopher:	How come?	
Simone:	Because, watch. If I was talking in here, then do you hear anything? [She walks her fingers across the bridge.] No, we don't!	
Christopher:	That's a great idea! But we need it longer, I'm asking. See, I think that's enough sprinkling.	Christopher redirects the conversation toward the *length* constraint, afforded by their
Teacher:	Do you have any ideas to make it long, Simone?	
Simone:	Maybe you could put some of these white pieces on to make it	

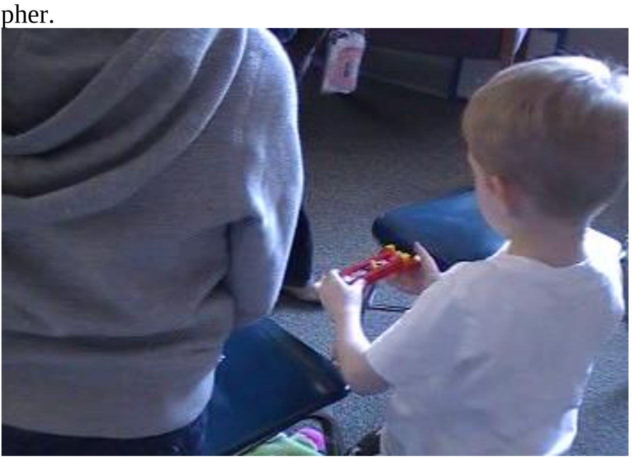
	longer. [She picks up the plates from the stairs.] Let's go, Christopher.	previous testing failures.
		
Christopher:	We're ready [to test]. Ooh, not even long enough. [The bridge is still too short.]	At the testing station, the bridge still does not meet the *length* constraint.
Teacher:	Oops. Ok, back to the drawing board. You dropped a piece.	
Simone:	I don't want the troll to eat the piece.	
Teacher:	So, what do you have to make sure that your creation is... what? And Christopher, those pieces aren't just there to put in [the bridge]. Those pieces are there to connect to things. So can you pick up the other pieces that Christopher is dropping? Because you guys are going to lose your pieces. Over there Simone, under the chair.	The sprinkles are removed, limited by the testing protocol and the teacher's suggestion.

Figure 10. Christopher and Simone revise and test their bridge, attending to legnth and strength as reinforced by the teacher and testing station, but also including constraints from the context of the story.

Christopher and Simone settled upon building a bridge, with each student constructing their own bridge section and subsequently trying to combine them (a frequent division of labor in young students). Their main design featured Simone's bridge deck, made of long beams, to which Christopher had added a set of stairs affixed to one end (see Figure 11). While Ms. Cook's addendum to the challenge statement was intended to emphasize the *strength* and *length* specifications, it also led to the unforeseen consequence of students attending to the *story* constraint in their bridge designs by exploring the role of the goats as users. For instance, Christopher's interpretation of the teacher's challenge clarification led him to incorporate stairs into his design, with the explanation that the stairs helped the goats to access the raised bridge deck by themselves.

Christopher and Simone's design was over-engineered for *strength*, and as a result the students were limited by the amount of remaining materials to make the bridge meet the *length* constraint. The physical joining of the two students' sections was also a weak spot in the design, but this problem was infrequently encountered during the testing protocol because the bridge usually failed to pass the *length* test first (see Figure 10, lines 1-4). Like Abed and D'Andre in the case above, Christopher and Simone also attended to the *emergent constraint* of *balance*, although not based on their own experience at the testing station. From his desk, located next to the classroom testing station, Christopher had noticed the difficulties other groups were having in balancing goats on their bridges. He adjusted his own design based on what he learned from other groups' test failures, adding walls to the deck of the bridge to keep the (round) goats from rolling off.

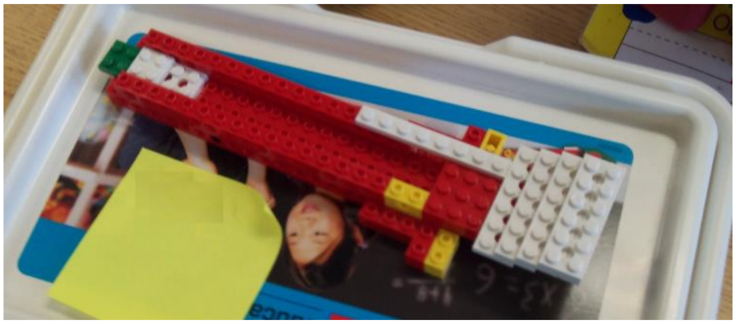


Figure 11. Christopher and Simone's bridge at the end of the first day. The structure consisted of a deck with walls and stairs at one end, to assist the goats. The connection between the deck and stairs was weaker, and the bridge was far short of the required length.

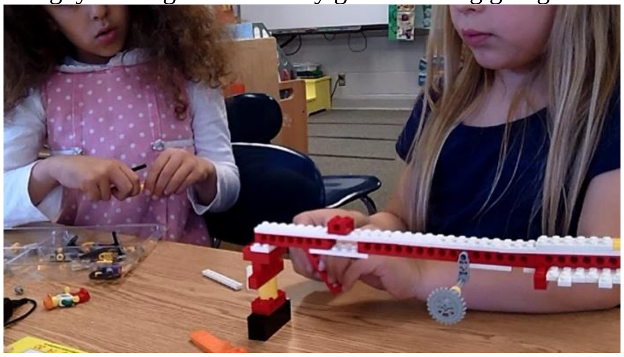
On the second day, as they struggled to make the bridge long enough to meet the *length* specification at the testing station. Simone proposed adding "sprinkles," or a layer of tiny LEGO® pieces from their kit, onto the deck of their bridge (see Figure 10, line 24). Simone then justified the addition of sprinkles by claiming they would make the goats' crossing quieter, and thus not alert the troll to their presence (line 27). This explanation was drawn directly from the context of the *story*, where the billy goats' "trip trapping" wakes the troll under the bridge. In response to questioning from Christopher and the assistant teacher, Simone demonstrated the effect of sprinkles, walking her fingers across the bridge, and concluding that they could not hear anything (lines 29-30). Christopher praised the sprinkles as a "great idea," but emphasized that their bridge still needed to meet the *length* specification (lines 31-32). However, when they attempted to test the bridge with sprinkles at the classroom testing station, Ms. Cook asked them to remove the sprinkles, as the pieces were spilling all over the floor and in danger of becoming lost (lines 42-46). Thus, the resources at the testing station, especially directives from the teacher, led to the removal of this *story*-based feature.

Christopher and Simone's early attention to the goats as users—from a *story* context (seen in their original airplane design, Christopher's staircase, and Simone's noise-dampening sprinkles) and a *balance* context (Christopher's additions of walls to keep the penny-roll goat from rolling off)—suggests that these students might simply have been more attentive to the context of the *story* than Abed and D'Andre in the previous case. However, within their activity system, attention to *emergent constraints* rooted in the *story* did not interact with the resources at the testing station; since they were not addressed by the testing materials or protocol, the systemic tension driving their design forward could not be resolved by meeting those constraints. Simone's sprinkles were short-lived as a design feature, limited largely by a tension with the teacher, when Ms. Cook ruled them impractical (for fear of losing pieces), and because the sprinkles did not contribute to meeting either *explicit constraint*. *Story* constraints that were not testable, via the testing protocol and testing materials as set forth in the lesson, were frequently abandoned, while some user-inspired features, like Christopher's stairs, persisted because they assisted in meeting the *length* specification. This case provides further evidence that the resources at the testing station afforded attention to *explicit constraints* such as *length* (the testing materials and protocol), and *emergent constraints* such as *balance* (through observing other students); however, *story* constraints were not persistent in student designs because the classroom resources (scaffolding from the teacher, as well as the testing materials and protocol) established a systemic tension which did not favor these *emergent constraints*.

Case 3: Fatima and Paige. Fatima and Paige also had the context of the *story* in mind from the very beginning of the challenge. Ten minutes into the lesson, when Ms. Cook surveyed the class to see what each group was planning to build, the girls announced that they were specifically building a "high bridge," to prevent the troll from reaching the goats as they crossed. As they built their high bridge and experimented with the available materials, they also added a small device designed to defend the billy goats from the troll (see Figure 12). Fatima and Paige frequently visited the classroom testing station and—encountering similar affordances as Abed and D'Andre from the testing protocol, testing materials, and teacher—they iteratively improved their bridge so that it became *longer* and *stronger*. Although they attended to these *explicit constraints* while building and testing, their bridge did suffer from structural integrity issues, partially due to the design decisions made to meet *emergent constraints*. Namely, in order to make a "high bridge" they built tall support columns on either end, which left the bridge not *strong* enough in the middle to support itself or the penny-roll goats; it was also difficult to *balance* the base of these columns on the testing station chair's curved edges.

Figure 12. Fatima and Paige's "high bridge," with support columns to raise the bridge up so the troll could not reach the goats, and a mechanism on the side (the gear) to protect the goats from the troll. The bridge was barely long enough to span the gap, and often slipped off the curved chair edges.

The girls persisted with their "high bridge" design into the second day, with their solution still not meeting the *strength* constraint (see Figure 13, lines 9-15, 22-23). At this point, another student in the class drew Paige's attention to a group at the testing station who had just successfully completed the entire challenge and allowed all three goats to cross on their bridge (line 32). Paige studied the other group's solution from across the room, and then suggested to Fatima that they should take the support columns off. When asked, neither girl was able to articulate why they had chosen to abandon the columns (lines 36-40), and instead explained how they were trying to meet the *length* specification by making the bridge longer. This shift away from the *story*-based constraint may not have been conscious on the part of Fatima and Paige, but it was precipitated from limitations provided by some resources within the classroom context: they were aware that another group had succeeded without accounting at all for *emergent constraints* such as the goats' safety from the troll, and the girls' attention to *emergent constraints* had made it too difficult to meet the challenge's *explicit constraints*, through material limitations and the design of the testing station.

Teacher:	What do we see? So, tell me now, what do you see, Fatima?	The testing protocols, materials, and scaffolding afford Fatima and Paige's observations about *length* and *strength*.
Fatima:	The bridge is long enough.	
Teacher:	The bridge is long enough. So now, what is our second test? That was our first test, to make sure the bridge is long enough. The next test is to make sure what?	
Fatima:	The billy goat can get across.	
Teacher:	The billy goat can get across. So, do we want to put the billy goat on our bridge? Ok, we're going to put the billy goat on our bridge.	
Paige:	[Places the smallest goat on the right end of the bridge. The bridge breaks and falls.]	
Teacher:	What happened?	Paige suggests a solution to make the bridge *stronger*, afforded by the building materials.
Paige:	It broke.	
Teacher:	Why did it break, I wonder. Think about it....	
Paige:	It wasn't sturdy enough.	
Teacher:	It wasn't sturdy enough. So, think about where your bridge broke.	
Paige:	We forgot a part that I need to build.	
Teacher:	Oh, so you should go think about the pieces that broke. And think about what you need to do to those pieces so it doesn't happen again. Because I love the length of your bridge, so now we have to think about how we can get this billy goat to stay on our bridge. Good? You guys have got some really good thinking going on.	
		
Paige:	[One column falls off, the bridge cracks in the middle.] Back to the drawing board.	Paige observes another successful test and affords her decision to remove their support columns, a user constraint afforded by the story.
Student:	One of the bridges holds all three [billy goats] together!	
Paige:	[Looks toward the testing area, and the successful bridge.] Wait, let's just try it like this, actually. [Takes columns off ends.]	
Fatima:	Let's test it like this.	

Teacher:	Before we do our goat test, is there anything you would like to change about your bridge to keep it from slipping? Ok, so far your length looks pretty good, but let's see what we can do to make sure it doesn't slip.	Afforded by the testing protocol and materials, and teacher scaffolding, Fatima identifies that the bridge is *too short*.
Fatima:	We need to make it longer.	

Researcher:	What are you going to do to make your bridge not slip?	Afforded by their testing results, students explain why they are making the bridge *longer*.
Fatima:	We need to make it longer.	
Paige:	We need this part. [Taking apart former columns to reclaim pieces.]	
Researcher:	You guys decided to take the legs off. Why did you do that?	
Paige:	Because part of it, we're making it, there's part of it. If we put on the second one, it might slip off, so we're making it longer. [Adds feet to the end of the bridge to extend it down and outward.]	

	Teacher:	Are you ready?	With affordances from the testing protocol, materials, and teacher, Fatima identifies that while their bridge is technically long enough, it needs to be *longer* still so that it will *balance* on the curved chair edges.
	Fatima:	We need it longer, because it's on the slippery side [of the chair].	
	Teacher:	Oh, so maybe you're saying, what, Fatima? You want to make what?	
45	Fatima:	The bridge longer, because it's slippery here [pointing to the edge of the chair].	
	Teacher:	When you look at the stream [the chair], it's going down a little bit. So to make it longer might make a difference.	
50	Fatima:	I just had a great idea! I told it! We need to make it even longer. It was only my brain!	

Figure 13. Paige and Fatima test and revise their solution, abandoning constraints rooted in the context of the *story* for those reinforced by the classroom testing station.

After removing the columns, their solution was more structurally sound, but they approached the testing station to find that the bridge was still too short (see Figure 13, line 32). The girls agreed that the bridge needed to be longer, and they returned to their desks to add bricks onto either side that extended the bridge slightly outward and downward (line 35-36, 38-40). Upon testing again, they found that while technically meeting the *explicit constraint* of *length*, their bridge would not *balance* by itself before the goats could be added, a pattern seen in Abed and D'Andre's iterative cycle. Fatima explained that they needed to make the bridge still longer, because it was sliding off the slippery edge of the chair (line 42). They continued iterating to make the bridge longer, with Fatima proud that she could diagnose the problem and propose a solution (lines 49-50).

Paige and Fatima began the challenge with a design that attended to not only the *explicit constraints* of *length* and *strength*, but also constraints tied to the context of the *story*, e.g., defending the billy goats against the troll. Like Abed and D'Andre, the resources at the testing station—the testing materials, protocol, and scaffolding from the teacher—influenced their revisions so that their solution also came to address the *emergent constraint* of *balance*, e.g., the systemic tension between their design and the testing materials was resolved by revising the design to make the bridge sit along the curved chair edges at the classroom testing station. Their design was improved iteratively to meet the *length, strength,* and *balance* constraints; however, their final bridge did not account for the context of the *story* at all. While the resources at the testing station did nothing to support the inclusion of pillars which were intended to make the bridge too tall for the troll to reach the goats (the troll did not factor into the testing protocol at all), the girls were not explicitly deterred from including them. The columns themselves were providing some tension within the activity system by making the bridge fragile and complicating the *length* requirement. Rather than the testing station, the tipping point that resolved this tension was another student's announcement of the first successful design at the testing station. Their observation of a design that did not include the *emergent constraint* of keeping the goats away from the troll directly preceded Paige's decision to remove the columns from their design; like Christopher and Simone, Paige was attending to the failures and successes of other groups at the testing station, and incorporating those observations into her design revisions. The bridge was not successful at meeting the *explicit constraints* before this point, and the testing station providing evidence that other students succeeded without the inclusion of *story*-based elements. From then on, their progression of revising their design based on *length, strength,* and *balance* followed a trajectory very similar to Abed and D'Andre's design iteration.

Discussion

To which constraints do students attend?

In my first research question, I asked: to which constraints do students attend when engaged in engineering design? Despite the teacher and lesson's emphasis on the challenge specifications, students in this lesson attended to both *explicit constraints*, and *emergent constraints*, which made the challenge richer and more closely resemble the experiences of professional engineers. Recognizing and designing for both technical and human-centered specifications is essential in engineering design practice (Jonassen et al., 2006; Zoltowski, Oakes, & Cardella, 2012). Engineering, as a professional practice, is grounded in context. Solutions are guided not only by physical specifications, but also by time, budget, and client constraints that dictate whether a solution is economical and feasible (Jonassen et al., 2006). The challenge statement for this lesson, and the *explicit constraints* of making a *long*, *strong* bridge, were not reliant on the story of the *Three Billy Goats Gruff*. Rooting the context of the challenge in a *story*, in which the characters and their struggles were familiar, afforded students' attention to *emergent constraints,* which they applied to their solutions of their own volition. Even before the teacher clarified the challenge statement to discourage the *motion* constraint, adding that the students' designs had to be useable by the penny-roll goats from the testing station, students had integrated the needs of the users in their designs, planning high bridges and other defenses against the troll's threat. *Emergent constraints* did not just include story context, but also the classroom context; the testing station, with the materials chosen to represent the stream and goats, afforded the attention to the constraint of *balance* by forcing the students to address the rounded edges of classroom chairs and round penny-roll goats in their designs.

Beginning designers have been described as interpreting design challenges as "straightforward, and a matter of comprehending the basic task and its requirements. By perceiving the design task as a well-structured problem and believing there is a single correct answer, they can act prematurely and attempt to solve it immediately" (Crismond & Adams, 2012, p. 747). In identifying additional constraints and incorporating them into their design solutions, the kindergartners in this study behave more like the descriptions of experienced designers, perceiving the problem space as open to interpretation and more likely to change or further define the boundaries of the problem space as they build and test (Adams, 2001). Contrary to the claims regarding beginning designers, these kindergartners exhibit an agency in their framing of the challenge which establishes their participation in the practices of the classroom.

What is the role of classroom resources and context in design iteration?

In my second research question, I asked: how are shifts in attention to these constraints *as* students iterate upon their designs related to the resources and context of the classroom? Older elementary students have been shown to engage in proficient problem framing (Roth, 1995), and consider multiple frames within one challenge when designing solutions—including the expectations of a classroom context, the needs of the user in the context of a piece of literature, and the functionality of their design within the context of the available materials (Hynes & McCormick, 2012; McCormick & Watkins, 2015). However, McCormick (2015) documented that students remained wedded to their designs during testing, even when they receive questioning from teacher. While Chapter 4 does corroborate this, in this chapter more often we can see that student attention to constraints and solutions evolve in tandem, as the students' engineering practices are mediated by the context of, and the resources provided within, the classroom, including teacher feedback. Attention to the *explicit constraints* introduced through the challenge specifications, and reinforced through the testing station and teacher scaffolding, led to students modifying their designs to remedy testing failures accordingly. However, because testing was source of systemic tension, it provided a major impetus for iteration upon a design solution; the constraints afforded by the testing station—*length*, *strength*, and *balance*—persisted in student designs, while those not afforded by, or limited by, the testing station—namely the *story* context—eventually vanished from student designs because they were not able to resolve that tension. It should be noted that in this lesson, the teacher played a large role in mediating students' activity, first providing affordances for the *story* constraints by clarifying the role of the goats as users within the challenge statement, but also in limiting *story* constraints by ignoring them at the testing station. Students' solutions were also mediated by the successes and failures of their classmates' designs at the testing station, applying these observations to their own solutions. Looking at the students’ progression through designing and redesigning their solutions, shifts in the activity system are mediated by those resources that can resolve the systemic tensions that arise between the testing station and challenge specifications, and the students' design solutions

Conclusion

This chapter presents two major findings. The first is that kindergartners proved able to handle complexity in design, particularly in defining constraints for their design solutions. While these kindergartners were given the *explicit constraints* through the challenge, they were also able to identify *emergent constraints*, especially those constraints afforded by classroom resources or the story context. The second is that the *emergent constraints* that survive the iterative cycles of testing and re-design are those afforded by the testing protocol, including the testing materials and teacher scaffolding.

In this classroom, the students were given what appeared on the surface to be a straightforward, non-subjective challenge with only two specifications: to make a bridge long and strong enough to support the billy goats as they crossed the stream. However, complexity was introduced implicitly by resources within the classroom context: in the materials chosen to represent the stream and the goats, by the material limitations imposed upon each group, by the perceived needs of the goats from the story as users, and through the dynamics between students and teachers. As a result, the students themselves not only attended to the *explicit constraints* of *length* and *strength*, but also identified and worked toward meeting the *emergent constraints* implicit in the challenge context. The assertion that beginning designers treat engineering design challenges as simple problems is belied by the rich contexts and various implicit constraints on their design students considered beyond those originally specified by the challenge.

Because *story*-based constraints were often abandoned before the end of the lesson, the depth to which students consider the role of the users in the problem and its constraints are hidden within the process of the students' iterative design cycles, and is not always evident in the students' final solutions. *Emergent constraints* that are of interest to students may not be anticipated or supported by teachers, and are not long-lived in the absence of classroom resources which afford student attention toward them, or limit student attention toward them. The role of the testing station in providing affordances or limitations on constraints, through the testing materials, testing protocols, teacher scaffolding, and peer observation, is explored further in Chapter 4. Through iteration, the balance of affordances and limitations leans toward the *explicit constraints*, those which were part of the teachers' lesson plan and preparation, and those *emergent constraints* that are both afforded by the building and testing materials and synergistic with the *explicit constraints*.

Implications and Further Work

This study has implications for teacher practice and lesson design, as these cases show the potential for encouraging student agency in defining constraints, if supported by classroom resources. While designing lessons, teachers should consider all possible resources in the classroom that might mediate students' attention to constraints, and also react dynamically to *emergent constraints* developed by students during lesson enactment. Presenting ill-defined engineering design challenges in the classroom requires proficiency in managing not only the *explicit constraints*, but also in remaining open and responsive to the *emergent constraints* students identify, and attended to, in their designs. Not providing testing environments which will present pushback on these *explicit constraints* will keep students from addressing those constraints when iterating upon their design.

Best practices of design pedagogy promote iterative processes driven by feedback from multiple perspectives, arguing that a better understanding of the problem and more self-exploration improves design solutions (Adams, 2001; Devon & Dorricott, 1996). In this way, providing the best environment in which students can attend to multiple *explicit* and *emergent constraints* is predicated upon establishing a challenge context in which students are free to frame and re-frame problems as they wish, and in which teachers find resources to provide affordances for varied student thinking. This study and earlier research on teachers from the same project (Kendall & Portsmore, 2013) show that teachers encourage *explicit constraints*, as well as implicit and testable *emergent constraints*, but discourage un-testable constraints (e.g., whether a LEGO® construction can fly under student power), or those that would conflict with the *explicit constraints*.

Teachers should be receptive to the specifications and constraints that students themselves bring to the challenge, working to support the students in their interpretation of the context while still holding them accountable through creating ways to evaluate their new features. One area in which *emergent constraints* could have seen more support in the classroom is at the testing station. The testing station established a protocol for assessing *length* and *strength*, and also *balance*, as it emerged from the representation of the problem at the station itself. However, once they identified various other *emergent constraints*, students did not always establish alongside them ways to assess whether their design operated within them. The cases in this study show that students do respond to feedback from resources at the testing station when revising their designs. Without this feedback, students may not have the impetus to improve upon designs which are not performing optimally, or recognize trade-offs between new constraints and old ones.

Chapter 4: Characterizing Students' Plan-Driven and Experimentation-Driven Approaches to Iterative Design Objectives and Activities

> Tinkering is a way of understanding difficult problems, of wrapping
> our heads around them and quantifying the unknowns.
> (Greenwood, 2011, p.3)

Two Approaches for Iterative Design

Frameworks for engineering education (International Technology Education Association, 2007; Massachusetts Department of Education, 2006; North Carolina State Board of Education, 2004) and engineering curriculum resources (Cunningham & Hester, 2007) almost exclusively promote a model of engineering design epitomized by a circular, top-down, and plan-driven process. As a result, teachers may only recognize and encourage engineering design practices based on the students' ability to build a functional design from an initial plan, or follow the steps of a modeled engineering design process in a specified, rigid order (Crismond & Adams, 2012; Hynes, 2012; Kendall & Portsmore, 2013; McCormick, 2004). Resnick and Rosenbaum (2013) argue that this plan-driven process is unnecessarily privileged in the engineering classroom, over bottom-up, experimentation-driven, "tinkering" style processes. When professional engineers operate in ill-defined and open-ended environments, their approach to design is more nuanced than a prescriptive process, and relies more on iteration than the traditional educational models of the engineering design process would imply

(Atman et al., 2007; Resnick & Rosenbaum, 2013). For ill-defined design challenges (Jonassen et al., 2006), where a variety of solutions and problem-solving processes are similarly possible, engineering design cannot solely be defined by the ubiquitous 5-step engineering design process.

While Resnick and Rosenbaum (2013), and Turkle and Papert (1991) assure us that successful students and professionals often do not prefer plan-driven processes for design, the engineering education literature still shows a preference for investigating that approach. Crismond and Adams (2012) question whether beginning designers even exhibit planning or sophisticated, top-down, iterative design processes; however, given the existence of alternative design approaches documented in the literature and professional settings, perhaps our focus should rest on documenting whether they too exist in early-elementary classrooms, and on whether the same component engineering design practices are utilized in diverse approaches to design. To that end, this chapter asks: how do students' activities and objectives differ through plan-driven versus experimentation-driven approaches to iterative design? I examine the objective of the students' activity while solving an ill-defined engineering design challenge in a classroom setting. Through case studies of three dyads, I provide evidence that young students do exhibit both plan-driven and experimentation-driven approaches to successfully improve upon their design solution. My case studies show that within these two approaches, students employ similar engineering design practices (such as testing and reflection), but toward different objectives.

Characterizing Approaches to Engineering and Science

Engineering education standards and curricula often suggest that engineering design is a circular process with a finite number of steps (Connolly, Jarvin, Rogers, Wendell, & Wright, 2008; Cunningham & Hester, 2007; International Technology Education Association, 2007; Massachusetts Department of Education, 2006; North Carolina State Board of Education, 2004). This plan-driven, top-down approach to design is almost universally presented as how "experts" solve engineering problems (Crismond & Adams, 2012). Proponents of constructionism, with the belief that knowledge is best gained through building tangible things, argue that bottom-up, "tinkering" approaches to engineering are valuable, productive, and even an innate way to engage in design (Resnick & Rosenbaum, 2013; Turkle & Papert, 1991). The idea of tinkering has been in the education research literature for several decades in the context of STEM education, and Resnick and Rosenbaum (2013) use a definition of tinkering that is particularly apt for this study: "a playful, experimental, iterative style of engagement, in which makers are continually reassessing their goals, exploring new pathways, and imagining new possibilities" (p. 164). In *Epistemological Pluralism*, Turkle and Papert (1991) explore what they call a “soft” approach to design, including concrete thinking in the form of *closeness* to an object, and *bricolage*, a “negotiational or contextual element” of the approach (p. 6). They argue that rather than viewing this soft approach as a precursor to the “hard” design thinking that professionals use, we should recognize it as a valid style of thinking in its own right, embracing a diversity of approaches as appropriate and effectual. In fact, many experts in design utilize bottom-up processes (Resnick & Rosenbaum, 2013), and when professional designers were surveyed about their understanding of the practice of design, often their answers contained themes of a creative process "guided and adapted by discoveries made during exploration," or "freedom to create any of an endless number of possible outcomes... within flexible and fluid boundaries" (Daly, Adams, & Bodner, 2012, p. 199).

For students especially, bottom-up processes can provide an alternate approach to engineering challenges where students build knowledge about a system in pieces and later assemble those pieces into a coherent solution. Preliminary research with high-school students shows tinkering can promote authentic disciplinary engagement, exploring physical systems, drawing connections to prior tasks, testing throughout the building process, using multiple strategies, building domain knowledge, and recognizing knowledge they did not yet have (Quan & Gupta, 2015). In museum education, researchers and practitioners at the Exploratorium in San Francisco are working on developing “Tinkering Learning Dimension Frameworks,” and similar tools for examining indicators of learning while making (Bevan, Gutwill, Petrich, & Wilkinson, 2014; Gutwill, Hido, & Sindorf, 2015; Petrich, Wilkinson, & Bevan, 2013). While these frameworks focus on tinkering or making in informal spaces, they share similar indicators with studies of engineering design practice, such as iteration, setting goals/posing problems, planning steps for future action, seeking feedback, and persisting after failure. They do point out that even though pedagogy has supported learning through making for decades (Dewey, 1933/1998; Papert, 1980), they still encounter pushback and doubt in the form of the question (and title of an article) “It Looks Like Fun, But Are They Learning?” (Petrich et al., 2013).

A similar distinction between top-down and bottom-up approaches exists in the domain of science, and has been the subject of more research than in the domain of engineering. Although science education researchers present an ideal model of inquiry as the goal of a classroom (Kuhn, 2002; Schauble, Klopfer, & Raghavan, 1991), "real" science is a lot less systematic, and does not always follow the model "scientific method" of generating a hypothesis and then designing an experiment to confirm it. Simon (1986) and Bauer (1992) noted that professional scientists generally specialize in theory or experimentation, with theorists tending to generate hypotheses and then conduct hypotheses-confirming tests, while experimentalists make data-driven discoveries by first collecting data and then finding the hypotheses with the best fit (Klahr & Dunbar, 1988). Klahr and others have described these approaches as a *search* through *dual decision spaces* (SDDS), with scientific theorists primarily concerned with search through the *hypothesis space* and scientific experimentalists exploring the *experimental space* (Klahr, 2000; Klahr & Dunbar, 1988; Klahr, Fay, & Dunbar, 1993; Li & Klahr, 2006; Zimmerman, 2000). Although arguably less efficient, as long as the search through the experimental space is systematic and thorough, valid inferences can be made, and correct hypotheses can be uncovered through inductive reasoning (Trickett, Trafton, & Raymond, 1998). Likewise, the SDDS framework could extend to engineering design, characterizing it as a search within two problem spaces: one space containing potential solutions (similar to the theoretical space) and the other containing the context, the constraints, and specifications of the challenge (analogous to the experimental space). Engineering design would then be the process of aligning these two problem spaces. Instead of presuming that engineering design will take the form of a rigid, plan-driven sequence of requisite steps, one can allow students the freedom to follow either traditional top-down, plan-driven processes—such as the model engineering design process—or bottom-up, experimentation-driven processes—like tinkering, depending upon the space in which they choose to conduct their search.

Identifying Student Activities

Activity theory frames students as engaging in activities and actions that work toward an object (or objective) and are mediated by contextual resources (Greeno & Engeström, 2014; Nardi, 1996). Using activity theory, one can describe different subjects engaged in the same activities in the same situation, but working toward different goals. To demonstrate this, Nardi (1996) provides an example:

> How do we account for variable responses to the same environment or "situation" without recourse to notions of object and consciousness? To take a very simple example, let us consider three individuals, each going on a nature walk. The first walker, a bird watcher, looks for birds. The second, and entomologist, studies insects as he walks, and the third, a meteorologist, gazes at the clouds. The walker will carry out specific

> actions, such as using binoculars, or turning over leaves, or looking skyward, depending on his or her interest. The "situation" is the same in each case; what differs is the subject's object. While we might define a situation to include some notion of the subject's intentions, as we have seen, this approach is explicitly rejected by situated action analysis (see also Lave, 1993). (Nardi, 1996, p. 42)

From an activity theory perspective, we can think of engineering design as the activity in which students engage while devising a solution to the design challenge, and of the many engineering practices in which they engage as the actions they take within that activity (Atman et al., 2007; Crismond & Adams, 2012; Katehi et al., 2009). Students engage in an iterative cycle of actions within the activity, and these practices fall under general categories of analysis (planning and reflective activities), synthesis (constructing a solution), and evaluation (testing the solution) (Smith & Tjandra, 1998). The previous example and the research presented in the above section suggest that students pursuing both plan-driven and experimentation-driven approaches to engineering design might engage in the same practices, but with different goals in mind—employing the same activities in the service of different objectives. Recognizing whether students are taking a plan-driven or experimentation-driven approach to engineering design involves more than noting the actions in which they are engaged, and instead requires that the goal of students' activity be identified.

Plan-driven approaches are characterized by a search through a design space, and the relevant research examines whether planning, sometimes more broadly contained within the practice of reflection, is driving the students' design process (Crismond & Adams, 2012; Schön, 1983; Watkins et al., 2014; Wendell et al., 2015). When discussing planning as one component of reflective decision-making at the elementary level, Wendell, Wright, and Paugh (2015) note that the practice includes brainstorming multiple ways to solve a design problem; reflecting on the constraints of the problem, scientific principles, and critiques of design options; and intentionally selecting which option to pursue. Research specifically on the benefit of planning for young designers has revealed mixed results. Rogers and Wallace (2000) showed that kindergarten students' drawings for planning were unrelated to their activities of constructing and testing, while Portsmore (2010) argued that first-grade students' successful solutions had a stronger relationship between the planning drawing and final artifact than less successful solutions. In order to describe a group's process as plan-driven, students must be observed using planning to drive the iterative improvement of their solution; the activity of planning (and subsequent reflection) determines the evolution of their objective through construction and testing of each planned modification to the solution.

Experimentation-driven approaches are characterized by a search through experimental space, which is achieved through experimentation (Adams, 2001; Crismond & Adams, 2012). Experimentation-driven designers might not initially have the domain knowledge (knowledge of the resources available, or engineering and scientific concepts) to devise a successful plan, and Crismond and Adams (2012) cite insights from experimentation as one way in which informed designers make knowledge-driven decisions about revising their design. Schauble, Klopfer, and Raghavan (1991) describe the engineering model of experimentation employed by elementary students engaged in engineering design challenges as aiming to "optimize a desired outcome" (p. 860). Rather than framing naïve engineering practices as plan-driven, they instead claim that the most effective approach for children is often to try various possibilities and see which works best. Johnsey (1995), in a study of pre-K through fifth-grade students, argues that students' initial drawing, an activity which is most often construed as planning, should instead be interpreted as the first prototype in a make-evaluate-make process. If this is true, further analysis of how students use the action of drawing—as a plan dictating their future constructions, or as vehicle for experimenting with design options—would be necessary to classify a student's objective or approach as plan-driven or experimentation-driven. An activity theory perspective, examining the student goals for activities such as drawing or testing, can help elucidate this question. In order to describe a group's process as experimentation-driven, students must be observed using experimentation to drive the iterative improvement of their solution; the activity of experimentation determines the evolution of their objective through optimizing features, and incorporating them into subsequent modifications of their solution.

Methodology

Study Design

This study focuses on a third-grade classroom, where the students were given the engineering design challenge to "throw a marshmallow as far as possible," based on a LEGO® WeDo challenge from the website *Dr. E's Challenges* (2014). The lesson was designed to integrate with a mathematics unit on measurement, via students measuring the distance of their marshmallow's flight and recording their data on a classroom graph. The challenge was also devised to have few constraints and one easily-testable requirement in order to promote iteration and simulate the ill-defined nature of professional engineering problems. The only specifications were that the students use a WeDo motor and battery pack (see Figure 14), and unlimited pieces from the WeDo building kits. Framing the challenge as a competition was intended to encourage continual improvement and iteration upon the students' solutions, and a classroom testing station was available during the lesson to promote frequent and non-subjective testing of designs. Groups received scaffolding in the form of an initial planning worksheet (see examples in the results section, Figure 16 below), which provided space for a sketch of their planned solution, and questions about how the solution would use the motor to achieve the challenge and what other pieces would be necessary. During the lesson, the two classroom teachers and the researcher circulated around the room to answer questions, ask the students about their solutions, and assist at the testing station.

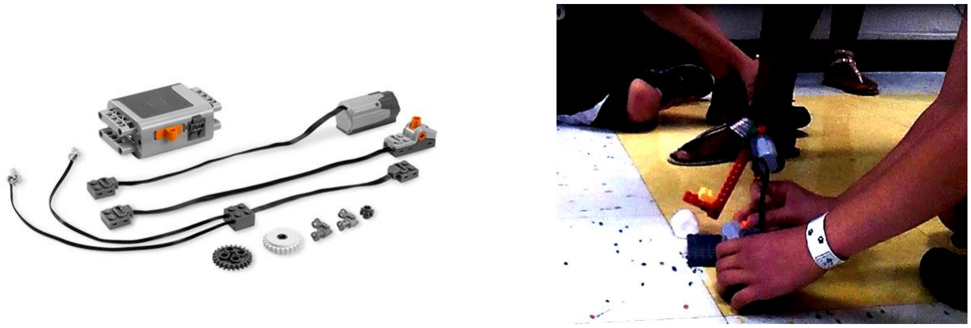


Figure 14. Students were required to incorporate the WeDo motor and power functions battery box, left, in their design. Right, students at the testing station in the hallway, using the linoleum floor tiles to mark every foot, and measuring inches with a ruler.

Participants

The research was situated within a third-grade classroom (ages 8-9) of 43 students with two classroom teachers, Ms. Bastille and Ms. Lyons. The classroom consisted of students from two classes, combined for weekly engineering lessons. The two classroom teachers were in their second and third year of participating in the larger, school-wide engineering education initiative, and thus possessed experience and confidence in enacting engineering design challenges. The researcher presented the challenge to the class and clarified any student questions. Three student groups, with three students each, are featured in this chapter: Hanna, Jackson, and Susan; Cameron, Jordan, and Kayla; and Chantelle, Sarah, and Thomas. With advisement from Ms. Bastille and Ms. Lyons, these students were chosen to provide a maximum variation sample of ethnicity, gender, and academic ability. Groups were formed at the teachers' discretion. Hanna, Jackson, and Susan took a very technical approach to designing, debating design choices and materials, and delegating responsibilities and work on subsystems. Cameron, Jordan, and Kayla worked more individually, and frequently proposed their own ideas and challenged each other’s. Finally, Chantelle, Sarah, and Thomas had a difficult time agreeing on anything, including which solutions to pursue and which materials to use.

Data Collection

Within this classroom, I chose to feature three groups in my data collection because I wanted more depth of understanding than capturing only fragments of each student in the class, and it allowed me to observe the students in the presence and absence of the teacher or other adults. Data was collected in several forms, through notes from direct observation of students within the classroom, photos of artifacts in the classroom, and the video recordings of the lesson from several cameras. Video data was captured with four video cameras, with three cameras and external microphones placed on tables where student groups were working, and a fourth filming the in-class testing area; at the end of the second day when the groups had finished construction at their tables, a second testing area was added in the hallway and two cameras filmed these testing areas, while I used a third camera to interview students about their test results. These data sources were chosen to gather evidence of dialogue among students, among students and teachers, and of artifacts created, referenced, and used by the students and teachers. The video recordings also captured the students' actions and manipulations of the materials, which were as crucial to the study as dialogue, because much of their discussion was highly contextual to the artifacts they were handling. Through this data, I assembled a holistic view of the classroom activity systems, including student interactions with people and artifacts, division of labor, and community rules and practices.

Data Selection and Analysis

I approached my research question by constructing a case study of each student group, identifying their engineering practices (activities) and the goals they were pursuing through these practices (objective). This account of the groups' pattern of activities, and their intent in engaging in those activities, allowed me to then categorize their approaches as either plan-driven or experimentation-driven. I first transcribed the videos for students' discourse, with annotations for their actions and manipulation of the materials. I then further annotated the transcripts line by line, to describe the actions being taken by the students (see Figure 15). This allowed me to create a narrative summary of the sequence of interactions and to capture the purpose and function of actions and dialogue (Derry et al., 2010). With help from this simplified account of the transcript, I employed Barab et al.'s (2002) methodology of isolating snapshots of actions (or sequences of actions) and framing them in terms of the engineering practices utilized by the students (see Figure 4 for example), thus creating episodes of iterative design cycles. "Illustrative examples" selected from these episodes, used as "grounded instances of course activity" (Barab, 2002, p. 86), are included for each case. For each episode, examining the actions taken by each group, and the objective of these actions, I could identify each group's engineering design process as plan-driven or experimentation-driven by determining whether the objective of their iterative cycle was motivated by planning, with iteration to achieve a functional prototype resembling that plan, or motivated by experimentation, with iteration to identify factors that affected the performance of their final design. For the Results section below, transcript excerpts were then chosen as narrative exemplars (Derry et al., 2010) of each group's approach.

Susan:	I think since the marshmallow is going to be on the arm, we should make a little holder [cupping her hands.]	S says arm needs holder for marshmallow.
Hannah:	I was thinking a box, like a square container. Like on a slingshot.	H thinks holder should be a square box, like a slingshot.
Jackson:	That holds marshmallows.	J agrees.
Susan:	That holds marshmallows to sling shot.	S agrees.
Hannah:	And draw the marshmallow there [points to the paper].	H tells S to draw marshmallow on plan.

Figure 15. An example transcript from the lessons, with line-by-line commentary summarizing, in simplified terms, the students' dialogue and actions.

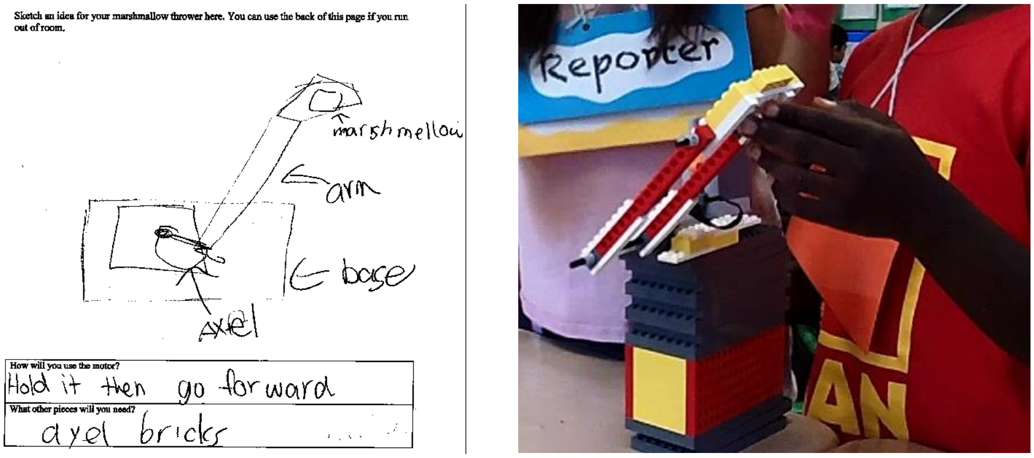
Results

Even before transcribing the video data, a clear difference emerged in the approaches of two of the student groups; one group began with a plan and constructed a prototype that was remarkably similar to their plan, while the other began with a design from a LEGO® WeDo instruction booklet and optimized it, through experimentation, to meet the challenge. The third group's approach was more complex, and I relied more heavily on analysis of the transcript and insight from the first two cases to assist in characterizing it. In my analysis, I explicate how each group's design approach was either plan-driven or experimentation-driven by focusing on the role of two design practices in iteration: reflection upon how a design meets the challenge specifications, and testing to improve the functionality of their design within the context of the challenge. Each of three groups is presented below as a case study.

Group 1: A Plan-Driven Approach

The first group, whom I called the *arm group*, consisted of Hannah, Jackson, and Susan. The *arm group* exemplified the engineering design process presented in K-12 standards, and, furthermore, approximated the cycles of design exhibited by professionals (as described by Atman et al., 2007 and Cross, 2000). From the minute their group formed, and continuing throughout the class, the objective of their activity was to construct the solution outlined in their initial plan; the actions they took to meet this goal lead them, through iterative cycles of testing and analysis, to a functional prototype of this plan, realized within the context of the classroom and materials available.

The key characteristic of the *arm group* that identifies their approach as plan-driven was the presence of thorough, up-front planning of their design. The group collaborated to scope out, draw, and label four subsystems in turn (the arm, base, marshmallow holder, and motor; see Figure 16 and Figure **17**), planning with the aid of the classroom handout. The four subsystems they identified during planning persisted throughout the process, suggested by references to the subsystems while later improving their design (examples concentrating on the arm and base in Table 4), and visually by comparing their initial drawing to the functional model (see Figure 16). This kind of planning practice has been described as a form of reflective decision-making (Wendell et al., 2015), and Valkenburg and Dorst (1998) describe a group of successful, college-aged designers engaged in a similar practice of naming several sub-problems while initially framing the problem, and then reflecting upon those sub-problems throughout the process.


Sketch an idea for your marshmallow thrower here. You can use the back of this page if you run out of room.

How will you use the motor? Hold it then go forward

What other pieces will you need? ayel bricks

Figure 16. Artifacts from the "arm group." Left, a drawing from the group's planning sheet. Right, the group's first fully-functional prototype. Note the striking similarities between the two.

Susan:	I have a good idea. An arm that shoots back.	Scoping arm design
Hannah:	[Simulates throwing motion with arm.]	
Jackson:	We could make it go one way, we could start at the back.	
Susan:	That's what I mean. You know how the motor moves back and forth? Since we hold it, we can make it go forward, since the motor connects to the axle. [Throwing motion with arm.]	Scoping motor/axle subsystem, connecting to arm
Jackson:	I literally just said that.	
Susan:	Whatever, I'll draw it. How do you want the base to be?	Scoping base to be rectangular, with layers of bricks to support the arm
Jackson:	How do you want the base to be?	
Hannah:	I think it should be like a triangle, maybe [holding hands in a peak].	
Susan:	How will you connect the arm?	
Hannah:	Oh, wait, no. A square, maybe. Like with a rectangle-square under it.	
Susan:	[Begins drawing.] Layers and layers of bricks so it can hold down without...	
Hannah:	Yeah.	
Jackson:	Without completely falling over.	
Susan:	I think since the marshmallow is going to be on the arm, we should make a little holder. [Making hands into dish shape.]	Scoping holder for marshmallow connected at the end of the arm
Hannah:	I was thinking a box, like a square container. Like on a slingshot.	
Jackson:	That holds marshmallows.	
Susan:	That holds marshmallows to slingshot.	
Hannah:	And draw the marshmallow there [points to paper].	
Jackson:	Ok, guys, are we ready?	

Susan:	Marshmallow [still drawing]. I know, I'm going. So the motor is supposed to be right here [points with pencil] and the little string that goes connected to there.	Finalizing details of the plan
Hannah:	That's supposed to be the axle [pointing].	
Susan:	[Clarifying.] So, you know that little wire that connects? And the axle.	
Hannah:	Oh, yeah.	
Jackson:	So, are we good?	
Susan:	[Still drawing/labeling.] So, that's the marshmallow. That's the arm. That's the base.	
Jackson:	Susan, are we good? I want to build.	

Figure 17. Susan, Hannah, and Jackson—employing a plan-driven design strategy by initially planning their design, including four subsystems: the arm, the base, the marshmallow holder, and the motor/axle attachment.

After recording their plan, the students' actions consisted of several different design practices through successive iterative cycles, which can be generalized by three steps. At the beginning of each cycle, the students identified and proposed solutions to problems, working within the subsystems from their plan, that were impairing their design's functionality. For example, when the arm would hit the table and break as the motor would turn on, they proposed raising the base higher so the arm could clear the table as it spun (see Table 7, Raising the Base). Students recognized when subsystems (such as the arm and the base) interacted with each other, and breaking the solution into subsystems allowed the students to set up a division of labor that attended to several problems with the design simultaneously (Jackson raised the base while Hanna and Susan fixed the arm). After implementing a solution, they would test the solution to ensure that the problem was resolved. The cycle continued through either addressing the same problem, if their solution had failed, or identifying a new problem within one of their design's subsystems. Two examples of this iterative cycle can be seen in Table 4.

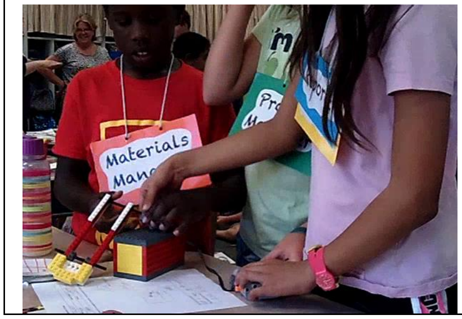
Iterative Cycle	**Identify a Problem**	**Propose a Solution**	**Test the Solution**
Building an Arm  	*Turns the motor on, the arm flips around on the table and falls off the base.* Jackson: Man! On the bright side, we made a blender. I think we need a new plan.	*Hannah suggests building an arm with an elbow, demonstrating with her arm.* Hannah: Yeah, I'm really saying that we should make it, like, another axle, so it can do that. Get an axle, and the same exact pieces you just got [for the bottom of the arm].	*Jackson adds the 'forearm' pieces, and they turn the motor on.* Jackson: Yeah, it should be able to. We can set it down like this, and when it turns on...Ah! *The arm flips around the table again.*
Raising the Base  	*The arm still hits the table when spinning, so they need a new solution.* Susan: You shouldn't have turned it on when we weren't finished yet.	Hannah: We should have it on a higher platform. We should raise a platform for it, if we can. Jackson: Oh, yeah. Hannah: That would be way better.	Jackson: I'll get a lot more pieces. *Jackson returns some time later with completed platform for base, which is more successful upon testing.*

Table 4. Two examples of the "arm group's" plan-driven iterative cycle: constructing a working arm, and raising the base to accommodate the arm's length.

The objective of the students' actions (practices) is consistent with a plan-driven approach to iterative design. They routinely worked from their initial scoping of the problem, were intentional in proposing solutions rather than experimenting to discover them, and in dialogue, referenced their plan and modifications, making them "work." As such, the group's activity can be described as a search through theoretical space to find solutions. The planning worksheet provided at the beginning of the lesson was probably not the only factor that influenced their decision to extensively plan their solution up front; however, it certainly provided scaffolding for their initial discussion of their solution, and referencing the subsystems as they refined their design. Additionally, their plan and discussions while iterating make it clear that some amount of domain knowledge—regarding the LEGO® materials and the functionality of catapults and similar machines—was necessary for students to create an initial plan that had any potential of being functional. Even so, the group did not possess enough domain knowledge to achieve success with their plans on the first try, and some amount of their iterative cycle can be described as "playing around" with the materials to make them behave as they desired. Thus, while we can describe this group as being plan-driven, they made extensive use of experimentation once their plans had been realized in physical form. The objective of the students' testing, which occurred after a new modification to the solution, was to verify that the physical realization of their plan was functional within the context of the materials at hand.

Case 2: An Experimentation-Driven Approach

The second group, whom I called the *leg group,* consisted of Cameron, Jordan, and Kayla. Their approach was characteristically experimentation-driven, as the objective of the students' activity was to take a design from a previous classroom lesson and optimize it for this context through experimentation. This group immediately asked the teachers if they were allowed to appropriate a design from one the instruction books they had previously used in class, a spinning leg intended to kick a soccer ball (see Figure 18). Their actions also included the practices of testing and reflection, but toward different aims than the *arm group*. With their functional but not-yet-optimized solution constructed, the *leg group* engaged in multiple, small-scale inquiry experiments, tinkering with the solution, to establish which variation was the most advantageous for their solution.

Figure 18. Artifacts from the "leg group." Left, an illustration of the kicking leg model from the LEGO® WeDo instruction booklet. Right, students experimenting with their model legs.

The students' iterative cycles can be generalized by a series of three actions. After targeting an *ad hoc* subsystem (as no such subsystems had been identified during an initial planning phase), the students first engaged in experimentation almost akin to scientific inquiry: identifying the factors which affected the distance their leg would kick the marshmallow (see Figure 18). Their process was similar to Schauble et al.'s (1991) description of naïve scientific inquiry of establishing the effect of each potentially important variable and making systemic tests of all feasible combinations; these students were fairly astute at isolating variables and explaining test results. For example, when the students experimented with the beginning position of the kicking leg, they started with the leg straight down, and compared it to the results of the leg beginning at 90 degrees, 180 degrees, and 360 degrees to determine whether this had an effect on how far the marshmallow travelled (see Table 8, Position of Leg). The position of the marshmallow or the kicking foot were not discussed during the initial phases of planning their design, or at any point up until the moment students began experimentation with those factors. These students' activity was playful and spontaneous, as tinkering is often described (Gutwill et al., 2015; Resnick & Rosenbaum, 2013), and instead of identifying a problem and proposing one solution at a time, the *leg group* treated their experimentation like brainstorming, attempting several experimental states proposed by each group member, and afterward identifying the most optimal result for that variable. Although the students were enthusiastic in pursuing their ideas, they responded to the failure of their experimentation gracefully; whichever test yielded the best result was finally implemented in their design solution without complaint. Two examples of this iterative cycle can be seen in Table 5.

Iterative Cycle	**Propose an *ad hoc* Subsystem**	**Experiment with Variable**	**Implement Optimal State**
Position of Marshmallow 	Kayla: Let's just test the marshmallow right now, see if it works. *Kayla gets a marshmallow from the teachers.*	Kayla: I have an idea! Can I please? *Kayla and Cameron try putting it on the table in front of the leg. Jordan tries throwing the marshmallow at the spinning foot.* Cameron: From the beginning, did you honestly think that was going to work? Jordan: Yes. oh, I got an idea. *Jordan tries smashing*	*Students continue trials with marshmallow on table, as this was the most successful method.*

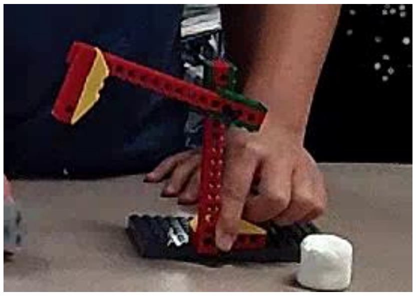
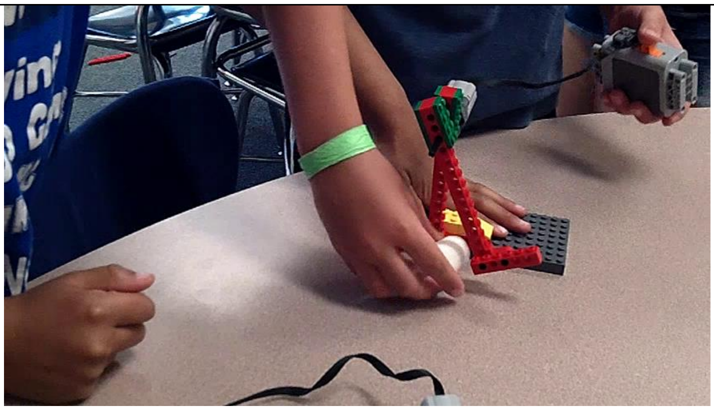
		the marshmallow onto the end of the foot. Jordan: Wait, I got an idea. Put it right there on top of the foot. *They try putting the marshmallow on top of the foot.*	
Position of Leg 	*While experimenting with marshmallow position, Cameron thinks to change the leg's starting position.*	*Original trials had leg starting at straight down position.* *Cameron cocks leg back 90 degrees before turning motor on.* Kayla: Oh, that was in the way. That didn't count. Cameron: Wait, it needs to go right there. *Cameron cocks leg back 180 degrees (pointing straight up) before turning motor on.*	Kayla: That went far. Cameron: Guys, let's go test it [at the testing station].

Table 5. Two examples of the "leg group's" experimentation-driven iterative cycle: investigating marshmallow position and leg position.

The *leg group*'s time for reflection came at the end of the second day, after they had achieved great success in kicking their marshmallow over eight feet—the class record. As they returned to their work space, I asked them what they had changed about their design preceding their last round of testing. The students all spoke at once, describing each subsystem and the testing, or failure, or sometimes accident, which led them to optimizing that aspect of their design. In those last two minutes, the students shared with me evidence of building their design from multiple pieces of knowledge (Bevan et al., 2014; Quan & Gupta, 2015; Resnick

& Rosenbaum, 2013), acquired through experimentation and rapid iteration, during the course of the lesson (see Figure 19 below).



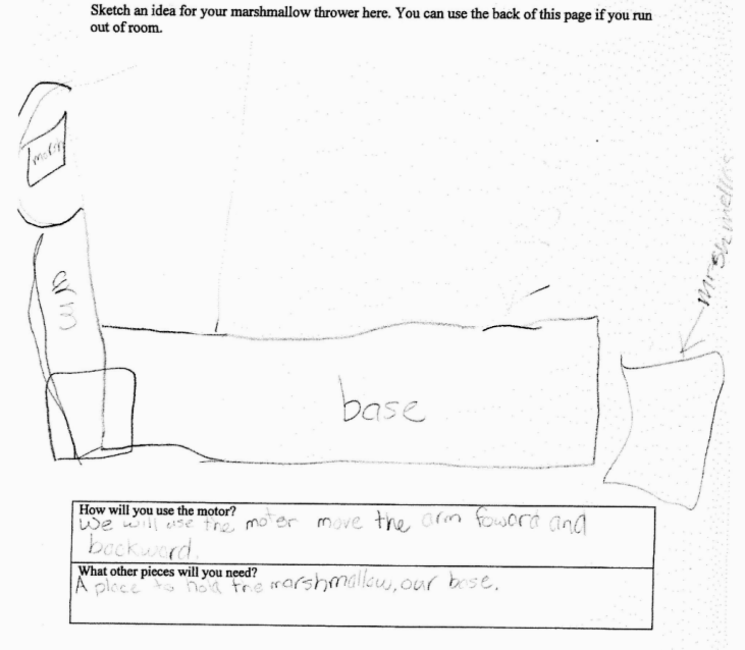
Teacher:	So, I want to know, tell me how it works.	Explaining foot shape
Kayla:	So, how it works...	
Teacher:	What did you guys change?	
Kayla:	We changed about it is less weight [on the kicking foot].	
Jordan:	Well, I had accidentally broke[n] [the foot], but then I thought about it, and I took the yellow piece off, and I took the other pieces off, and when we did that, we did this [Indicating their final foot shape].	
Cameron:	We wanted [the marshmallow] on its rolling side.	Explaining marshmallow position
Jordan:	We put [the foot] right there [behind the marshmallow] and it increased more speed and went faster and went like this [rotate the foot around 360 degrees before hitting the marshmallow].	Explaining foot position
Kayla:	And we also changed that we made the foot pointier because the pointier it is, the farther [the marshmallow] will go.	Explaining foot shape
Jordan:	So, let's try it.	Demonstration
Teacher:	Do you want to hold onto the base?	
Jordan:	Yes.	
Cameron:	Yeah, we—also it needs to be on its rolling side because it will just skip like that [on its flat side], it will slow down. But if it's on its rolling side, it's like a barrel, it can roll. [Turns on motor, marshmallow is kicked away.]	Explaining marshmallow position
Teacher:	Pretty good!	Demonstration and troubleshooting marshmallow spinning
Jordan:	It spun!	
Cameron:	But the reason that it spun, it was too much on one side than another.	
Teacher:	Yeah, so [the marshmallow] needs to be in the center of the foot.	
Cameron:	Yeah, but it was really cool. Do you want to see? It's going to go farther this time. [Resets marshmallow, foot. Turns motor on, marshmallow is kicked away.] It went farther.	

Figure 19. The "leg group"—Cameron, Jordan, and Kayla—exhibiting their bottom-down design strategy by explaining the investigations which led them to identify the most optimal configuration for their prototype.

The objective of the students' actions (practices) is consistent with a bottom-up, experimentally-driven approach to iterative engineering design. The dialogue throughout the lesson reflected their experimental stance when announcing a "new idea" for which variable to manipulate, or asking for access to the solution so they could "see" or "try" something (see Table 5.). Unlike the *arm group*, who proposed large design changes more or less one at a time, the *leg group* picked a subsystem to vary and conducted several small-scale tests all at once, so they could choose the most optimal way to redesign. As such, the group's activity can be described as a search through experimental space to find the best solution Additionally, analysis of the *leg group's* discussions makes it clear that the students were building domain knowledge as they interacted with the materials and revised their solution. Their decision to begin from a familiar LEGO® model, rather than design a solution from scratch, allowed the group to focus on the physics of the challenge—the speed of the foot, the force imparted from the kick, and the subsequent motion of the marshmallow—rather than how to make the materials conform to a previously conceived design. Their experimentally-driven approach ultimately led to an empirically developed solution, with design choices that could be explained and defended.

Case 3: A Hybrid Approach

I named the third group, consisting of Chantelle, Sarah and Thomas, the *hybrid group* because their process contained elements of first plan-driven and then experimentation-driven approaches, with mixed success. Initially, the group agreed on a plan that they described as a catapult, recording it on the planning worksheet. Through the scoping of their design they identified many subsystems, including a base, arm, and holder for the marshmallow, but did not attempt to incorporate the motor until the very end.


Sketch an idea for your marshmallow thrower here. You can use the back of this page if you run out of room.

How will you use the motor?
We will use the moter move the arm foword and backword.

What other pieces will you need?
A place to hold the marshmallow, our base.

Sarah:	We should have our base, like, at the bottom. [Begins to draw.]	Scoping base.
Chantelle:	Ok. We could make a foot! [Also begins to draw on planning sheet.]	Scoping arm.
Thomas:	We need a catapult! Don't kick it. How do you kick it? We need to throw it.	
Sarah:	[Inaudible] like that.	
Chantelle:	Why can't we kick it?	
Thomas:	Because it goes farther if you throw it.	
Chantelle:	Ok. [Erases foot from plan.]	
Sarah:	So, a catapult.	
Chantelle:	So, we can kind of keep this [the throwing arm], but make it a little shorter. Because, you know, what a catapult is like [finishes erasing, then starts drawing]. Ok, I know how a catapult can be. We have, like, you know them blue things [referencing LEGO® pieces]? We can have that and it could just hang down. And you know, we have something that, like, you have like a stick, and we just hit it up, and it will throw.	Scoping marshmallow holder and arm mechanism.
Sarah:	Our motor needs to be somewhere down here [draws a box at the base of the arm.]	Scoping motor location.
Chantelle:	And the marshmallow is going to be up here. You know, it goes farther than what you think. [Draws marshmallow to right of catapult, after it has been thrown.]	Scoping marshmallow holder.
Sarah:	[Labels base, arm, marshmallows on drawing.] We need to go	Scoping motor

	show this to Ms. Bastille. [Reading further questions on planning sheet.] "How will you use the motor?" We will use the motor to move the arm forward and backward [Writing the answer.]	function.
Chantelle:	Forward and backward.	
Sarah:	[Reading the next question.]"What other pieces will you need?" A place to hold the marshmallow.	Scoping marshmallow holder.
Chantelle:	Oh, we need a place to hold the marshmallow, and a...um....	
Sarah:	A place to hold the marshmallow, and our base. [Writes the answer. Instructs Thomas to start getting pieces, including a big grey piece for the base.]	Scoping base.

Figure 20. The "hybrid group's" plan-driven approach to plan the subsystems of their design.

As they built, the group's design choices were often well-informed, with Sarah describing how the catapult arm should be longer, because a marshmallow thrown from a taller height would travel farther before hitting the ground. The *hybrid group*, however, seemed to lack the knowledge or experience necessary to realize their design solution with the materials provided and required, such as connecting the arm to the motor so that it would spin (see Table 6). After many minutes of frustration, the group received scaffolding from the classroom teachers, suggesting that they experiment with the motor, consult the LEGO® We Do instruction booklets, or observe the designs of other groups who had functioning models in order to gain this knowledge. The group tried to realize their initial plan, but the mediation of the materials, the teachers, and their own expertise was not successful in making their solution from their plan functional.

Iterative Cycle	**Identify a Problem**	**Propose a Solution**	**Test the Solution**
Testing the Arm	Chantelle: That's never going to work. *They turn the motor on, but it does not spin the arm.* Sarah: How do we make it so [the arm] turns?	Thomas: To make it stay, we need one of those grey pieces. *Thomas leaves to get a new piece.* Sarah: Maybe if we go...	*Sarah turns the motor on again, but the arm still does not move.* Chantelle: We can make the legs. We don't have to use that piece, Ms. Bastille said.

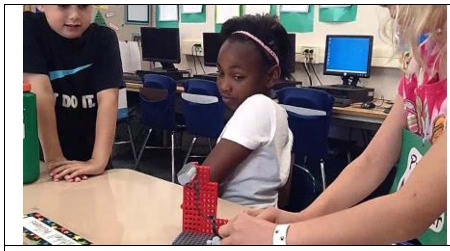
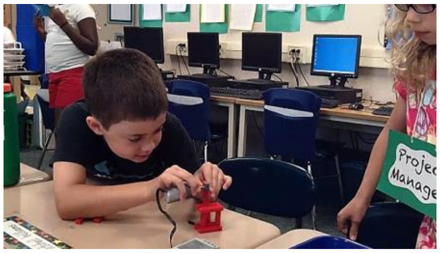
		*Sarah adjusts how the arm is connected to the motor.*	*Chantelle suggests trying a different design.*
Iterative Cycle	**Propose an *ad hoc* Subsystem**	**Experiment with Variable**	**Implement Optimal State**
Experimenting with the Motor 	*Thomas returns with new piece to connect the motor to the arm.* Thomas: This piece.	Thomas: I want to see if this works. *Thomas removes the marshmallow holder from the arm, and attaches it to the motor with the new piece, isolating that subsystem for experimentation.* Sarah: We should do something like that.	Thomas: It could work, or we can make [the legs]. I don't care. *Turns motor on, marshmallow holder spins.* Chantelle: Oh! Ms. Bastille!

Table 6. Two examples of the "hybrid group's" iterative cycle: first following a plan-driven approach, and then adopting an experimentation-driven approach due to lack of knowledge of the materials.

Frustrated with a lack of progress and with the class half over, Chantelle advocated for building the kicking foot model from the instructions (see Table 6, Test the Solution) as the *leg group* and several other groups had done by this point. Thomas, however, in order to incorporate a new piece, deconstructed their original catapult model, and stated that he wanted to "see if it works" (see Table 6, Explore through Inquiry). Here the group's approach shifted away from plan-driven, inspired by Thomas' belief that this new material (a LEGO® piece) would allow them to couple the motor to the rest of the solution, as Sarah and Thomas began to tinker with just two subsystems of their previous design, the motor and the box-like holder for the marshmallow, ignoring for a moment the arm and base subsystems. The group played with their new working prototype, experimenting with ways to make the holder rotate with the motor, subsequently investigating various ways it could be mounted onto an arm, and finally adding an appropriate base.

While the students' actions were initially working toward physically constructing their plan, they were not able to realize this plan with the domain knowledge they possessed of how the LEGO® motor worked, and incorporating the motor was a requirement of the challenge. Switching to an experimentation with materials they believed would work, they discovered a way to make one subsystem functional, and then worked backwards, adding subsystems to the design that accommodated this functional core. Their process became experimentally-driven, dominated by changes that built on what was already functional. Their final, experimentally-driven approach echoes Turkle and Papert's (1991) description of a *bricoleur* "scultping" their computer program.

> Anne does not write her program in "sections" that are assembled into a product. She makes a simple working program and shapes it gradually by successive modifications. She starts with a single black bird. She makes it fly. She gives it color. Each step is a small modification to a working program that she has in hand (pp. 9-10)

Similarly, the *hybrid group* begins with this functional core and builds up a solution around it, possessing a relationship with the materials and physical solution, rather than constructing the original base, arm, holder, etc. from their initial, abstract plan. From this relationship and immediate feedback while building, they are able to gain knowledge of how the materials work as they go.

Discussion

Plan-Driven and Experimentation-Driven Approaches

My research question asked: how do students' activities and objectives differ through a plan-driven versus experimentation-driven approach to iterative design? The data show that even young students engaged in the activity of iterative engineering design employ both plan-driven and experimentation-driven approaches to designing, and frequently both during the same challenge. This is to say student objectives included the realization and testing of a planned solution constructed with the materials available, and a search for an optimized solution through experimental manipulation of a pre-existing design, both in order to meet the given engineering design challenge. But despite differing objectives, both approaches utilize the same kinds of engineering practices (actions).

Tinkering has been dismissed as simply "play" (Petrich et al., 2013; Resnick & Rosenbaum, 2013). Based on the literature, standards, and curricula for engineering education, teachers are likely to consider student success through the functionality of their solutions, but also emphasize a prescribed sequence of engineering practices, resembling the simplified model of the top-down, plan-driven engineering design process (Hynes, 2012; Kendall & Portsmore, 2013; McCormick, 2004). Instead, this study provides examples of how successful solutions can be achieved in the early-elementary classroom through either a plan-driven or experimentation-driven approach, when the lesson is ill-defined and students are free to explore not only theoretical but also experimental space. Turkle and Papert (1991) describe the work of *bricoleur* programmers, who have a negotiational relationship with their code, but claim "the final program produced by a *bricoleur* can be as elegant and organized as one written with the top-down approach....the difference between planners and *bricoleurs* is not in quality of product, it is in the process of creating it" (pp. 9-10). Through the examples in this study, practitioners should be reassured that even young students can employ essential engineering practices—knowledge-building inquiry toward designing a successful solution, and reflection on the functionality of the solution and the process used to design it—no matter their approach.

Just as in the Nardi (1996) example of the nature walk, this study provides evidence that students may journey through a lesson with different objectives through either plan-driven or experimentation-driven approaches, but they will still employ similar practices (actions) to that end. Cunningham and Carlsen (2014) critique documents like the Next Generation Science Standards (2013) that treat engineering "core ideas" as content, when they are in fact practices, and they argue that this classification trivializes engineering as knowing the definitions to terms like "optimization" and being able to "order the steps of the engineering design process" (p. 199) rather than proving competence in engaging in engineering practices. In classrooms, Schauble et al. (1995) caution against the fragmentation of scientific experimentation into skills that lack coherence and meaning when isolated from the actual practice of inquiry. Crismond and Adams

(2012) suggest that teaching decontextualized process skills can lead students to treat them as perfunctory, rather than appreciate their individual contribution to the process of design. If young designers gain experience with similar engineering practices while employing both plan-driven and experimentation-driven approaches, then neither need be privileged in the classroom, and teachers should feel free to provide ill-defined challenges, akin to professional contexts, where it is natural and productive for students to use and improve such skills.

Engineering Practices

Reflection, like the reflective decision-making described by Wendell, Wright, and Paugh (2015), occurred during the initial planning as well as during testing and redesign, and encompassed essential design practices for both approaches. However, the most influential reflection occurred at different points in the process for each group, and helped to differentiate the two approaches. In both the plan-driven and experimentation-driven cases, reflection allowed students to demonstrate awareness of the steps they would follow in their process for designing the solution, and any domain knowledge applied to the construction of the solution. For the *arm group*, whose major reflection took the form of planning, they exhibited at the beginning of the process a knowledge of the parts of a catapult and LEGO® materials. Conversely, the *leg group* engaged in significant reflection at the end of the process, where they were able to describe each experiment, mistake, and conjecture which had led to their design decisions and their solution's performance. Both of these groups, of course, made use of reflection through testing, analysis, and redesign of their solutions throughout their iterative cycles, but testing served a different purpose for plan-driven design than it did for experimentally-driven design. The knowledge required to make a winning design was gained by the *leg group* through iterative cycles of experimentation, while the *arm group* used testing as a way to implement the four subsystems of their design in a functional way within the context of the classroom (materials available).

The *hybrid group's* approach initially mirrored the *arm group*, but ended more closely resembling the *leg group*. They engaged in reflective decision making up front, but were not successful with a plan-driven process because they lacked the domain knowledge of LEGO® materials, specifically the motor, to implement their plan. They found more success through an experimentation-driven approach, by deconstructing their first design and experimenting incrementally with each subsystem as it was re-introduced. Thus, reflection as the students built and tested the solution informed their subsequent revision and design choices. This is further evidence that experimentation-driven processes, or goal-driven tinkering, can be a useful way for students to improve familiarity with the domain knowledge necessary to construct a functional design, even when they are not able to apply that knowledge toward planning, or realizing a plan, at the beginning of the challenge. The teachers in this case did a good job of suggesting ways for the students to increase their domain knowledge through alternative approaches to solving the problem (observing another group's solution, borrowing from the completed solution for another lesson, and tinkering with the materials to better understand them). Teachers should be prepared to suggest alternative approaches to groups, so they can scaffold activities in the classroom when students may have insufficient domain knowledge to initially implement successful design planning.

Implications and Future Research

Crismond and Adams (2012) claim "beginning designers feel that understanding the design challenge is straightforward, and a matter of comprehending the basic task and its requirements. By perceiving the task as a well-structured problem and believing there is a single correct answer, they can act prematurely and attempt to solve it immediately" (p. 747). However, both the *arm group* and the *leg group* showed a more sophisticated approach to solving the design problem. For the plan-driven approach, the students did a thorough job of scoping out subsystems during the initial planning stage. However, they left many specific details of their design undefined until they had completed several iterative cycles, implementing the design with the materials available and testing its functionality, just as professional designers would (Valkenburg & Dorst, 1998). The students who took an experimentation-driven approach also did not perceive the challenge as well-defined, instead beginning with an initial conceptual solution for kicking the marshmallow, and searching for an optimized solution through experimentation. Both of these approaches are consistent with other research that suggests elementary students possess higher developed design practices than previously thought, particularly when engaged in open-ended challenges (McCormick & Watkins, 2015; Watkins et al., 2014; Yang, Johnson, & Portsmore, 2015).

Future research should shift its focus away from only the traditional, plan-driven engineering design process, and recognize that experimentation-driven methods and tinkering can be valid and successful approaches. For young students, planning in particular should be examined as just one facet of student reflection, which can occur at multiple points within the design process, and is highly dependent on whether students have the domain knowledge to solve the design challenge up front, or must collect it as they go. Resnick and Rosenbaum (2013) give suggestions for designing contexts for tinkerability, such as encouraging students to document intermediate stages and failed experiments, promoting exploration and collaboration through use of classroom space, and combining diving in (experimentation) with stepping back (reflection). Bevan et al. (2014) provide frameworks for evaluating dimensions of learning during tinkering and making, albeit in an informal, museum environment. These contexts and frameworks should be verified for early-elementary grades with empirical classroom studies, and implemented in engineering design lesson planning. Most importantly, standards and lessons need to support teachers in more open-ended contexts where student approaches to design will be more variable, and tools must be developed for assessing design practices beyond memorizing definitions and ordered steps in a cycle.

Conclusion

This chapter provided several important findings. The first is that young students, in this case third-graders, can employ both planful and *bricolage* approaches to design; both approaches allow students to successfully engage in the knowledge-building and iterative improvement necessary to construct a solution. Students engaged in tinkering do learn, and students without sufficient domain knowledge may require time to tinker in order to build the knowledge base required to be planful later. Regardless, the connection between knowledge and engineering practices happens in both the planful and *bricolage* approaches, but the timing of the reflection on that connection differs: planners reflect while engaged in iterative planning of solutions, while *bricoleurs* reflect at the culmination of the process when they summarize the tinkering and experimentation that led them to their final design. In light of these findings, I reiterate Resnick's assertion that neither plan-driven nor *bricolage* approaches should be privileged over each other in the classroom; both serve design and learning and should be encouraged and supported.

In taking diverse approaches to engineering design, these students showed that they were able to recognize the complexities of the design challenge, and were not afraid to tackle these complexities in managed pieces. Such challenges and opportunities to tinker and gain knowledge may be especially beneficial for beginning designers, and as a result, teachers should not hesitate to enact lessons with challenges that will require students to improve skills or acquire knowledge, rather than challenges using prior knowledge. Teachers will need to possess some confidence and domain knowledge in the materials and classroom engineering themselves in order to make those challenges successful experiences for their students. This recommendation has implications for evaluating student design processes, since many teachers and curriculum offerings emphasize planning as an essential design practice. While this specific practice, in isolation, is not useful to all students depending on their prior knowledge or preferred approach to solving design problems, reflection upon product and process at any time during the lesson, and experimentation to improve the solution, are valuable to student success.

Chapter 5: Examining Lesson Criteria for Encouraging Iterative Design

> Failure is instructive. The person who really thinks learns quite as
> much from his failures as from his successes.
> (Dewey, 1933/1998, p. 142)

Introduction

Iteration, or making incremental improvements during the development of a solution, is one of the defining features of engineering design, and results in deeper understanding of concepts and better quality solutions (Atman et al., 2007; Atman et al., 2005). In this way, design has been described as a progression through levels of understanding, from the abstract to the concrete (Adams, 2001; Goel & Pirolli, 1992; Hybs & Gero, 1992). The iterative, cyclical nature of design is symbolic of design not only as a process of improving upon a solution, but also as a process of personal learning (Kolodner, 2002; Kolodner et al., 2003; Papert, 1991). Driving these iterative cycles of improvement is the practice of impartial evaluation of a solution, otherwise known as testing. Designers utilize testing to identify any deficits in the solution's performance relative to the challenge specifications, providing them with an opportunity to analyze the cause of the deficits, and propose a solution to correct the deficit. Evaluating and improving a solution is a complex behavior, making use of complex skills such as analysis, evaluation, and creation, and is likely the source of iteration's conceptual and design benefits for students (Adams, 2001).

With the adoption of engineering design in K-12 curricula, the opportunity for applying higher-order thinking skills through design iteration will be attractive to teachers. My work has been primarily focused on early-elementary classrooms (Kendall, 2015, Forthcoming; Kendall & Portsmore, 2013; Wendell et al., 2014), where there is no prominent research about how young students engage in the evaluation and improvement of their design solutions through iteration (Crismond & Adams, 2012; Katehi et al., 2009). Andrews (2014) demonstrated that while older-elementary students may not appear that their design is informed by failures, a more fine-grained look at transcripts reveals clues that they are thinking logically about the results of their testing. Lottero-Perdue and Parry (2017) examine elementary teachers using failure language in the engineering classroom, but have little to say about the resulting activities of students themselves.

In Chapter 2, I proposed four lesson criteria for encouraging students to engage in iteration while designing. These criteria were applied in varying degrees to all four lessons in this study, and appeared to result in several successful classroom experiences in which practices related to iteration, through cycles of testing and revision, could be explored. In Chapter 3 of this dissertation, I examined shifts in students' attention to design constraints as they iteratively improved their solutions, in which the testing station provided a tension between the *a priori* specifications of the challenge, and the objectives of the students, reinforcing those specifications throughout the iterative cycles. In Chapter 4, I presented examples of iterative design cycles undertaken in a challenge with few constraints, which allowed students the freedom to explore both plan-based and experimental-based approaches while still engaging in several important engineering practices. This last empirical chapter examines, instead, two lessons in which students exhibited infrequent and less-productive iterative cycles. In these cases, students did not frequently test or revise their solutions, and I seek to answer the question: how do the four lesson criteria introduced in Chapter 2 influence the students' iterative activities of testing and revision? From a situative perspective, I describe the affordances and limitations[4] of these lesson criteria in promoting iteration by describing the classroom resources they establish, and how those resources mediate the students' and teachers' classroom activities. This has implications for lesson design by also identifying where these lesson criteria succeeded and failed in their intent to promote iteration.

Previous Research

Iteration

Iteration is a key step in the engineering design process, critical to optimizing design and one of the behaviors that distinguishes engineering from other pursuits such as scientific inquiry (Brophy et al., 2008; Katehi et al., 2009). Proficiency in finding solutions to problems is described as an ability to recognize dissatisfactory states and transform them into satisfactory states (Adams, 2001). Few problems are solved in only a single attempt, underlying the necessity for engineering design to operate in iterative cycles.

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[4] The literature generally refers to resources as either *affordances* or *constraints.* I use the term *limitations* rather than constraints in order to avoid confusion with the engineering terminology.

Lesson Criteria for Iteration. As detailed in Chapter 2, the teachers in this study were asked to plan their lessons to meet certain criteria, in order to ensure that the students would have the opportunity to engage in iterative design. Two of these criteria had to do with specifications and testing, that the challenge has "definable and non-subjective specifications," and that "testing and re-design are explicitly encouraged by the structure of lesson and classroom." Authentic engineering challenges often incorporate "subjective" specifications (Jonassen et al., 2006); clients generally desire not only functional buildings and bridges, but also aesthetically pleasing ones. But while beauty is in the eye of the beholder (and further complicated by classroom clients in the form of fictional characters), focusing on definable, and even more quantifiable binary (*Does it hold the weight, yes or no?*) or measurable (*What is the maximum distance it will travel?*) specifications gives the students a goal toward which they can improve their design, and likewise goalposts that teachers may move during the lesson, if necessary. Because engineering design challenges do not necessarily have a "correct" solution, as is the case with ill-defined problems, whether a solution is dissatisfactory or not can only be determined by how it performs in testing (Jonassen, 1997). Thus, specifications and testing go hand-in-hand, and when a specification is introduced to the challenge, it should be accompanied by an appropriate testing protocol and metric for success. As discussed in Chapter 3, testing provides one kind of systemic tension within a students' activity system that serves as an impetus for a shift in objective, and thus a revision in the design solution.

The lesson criteria from Chapter 2 also suggest that design challenges allow for students to have "a role in defining the problem," and that the challenge not be "over-constrained." The last two criteria are synergistic, insomuch as leaving aspects of the challenge open allows students the opportunity to define those aspects for themselves. This includes asking for student input on any of the contextual details of the classroom and challenge: e.g., defining specifications for the solution, determining the constraints on the challenge, suggesting protocols for testing solution specifications, choosing materials for construction, and proposing the needs of users or clients. Research and experience suggest that these criteria will encourage iteration, but they have not been extensively studied at work within the elementary classroom. This chapter will explore how they work to afford iteration in student designs, and how the criteria can be applied to engineering design lessons to afford iteration.

A Situative Perspective

Borrowing from activity theory, researchers can document the resources in a classroom that mediate a students' actions. In this case, the classroom has an abundance of contextual and environmental factors—such as building materials, curriculum materials, testing stations, peer and teacher interactions, and classroom norms—which mediate the students' engineering practices such as testing and revision. Knowledge in activity theory is framed as participation an activity, with learning indicated by resolving tension between the subject and the activity system, shifting the objective of one's activity, and assuming agency and motivation through one's role in the community (Barab et al., 2002). In my analysis, I will be identifying the resources and aspects of the activity system that result from the four lesson criteria and investigating their role in promoting iteration by mediating shifts in the students' design and activities. During the episodes when students are not observed testing and revising their designs, I will examine the reasons why tensions that would afford students to iterate were not set up by the activity system, and how this could be remedied by making changes to the curricula.

In this study, teachers were asked to develop a lesson following the criteria for iteration found in Chapter 2, and then enact that lesson with their students. The teachers' objective for each of these lessons was for the students to meet the specifications for an engineering design challenge, while incorporating standards from the general curriculum. However, the teacher cannot fully predict the implications their choice of instruction, materials, scaffolding, student interaction, and any number of resources will have for how the students perceive the lesson and its objective, and whether or not they iterate upon their solutions. Thus one can think of the teacher's intent as the *planned* curriculum, the events as they happen in the classroom as the *enacted* curriculum, and the *experienced* curriculum as the way students participate in the lesson (Marsh, 2009). Recent education studies describe a construct called the "learning object" (Greeno & Engeström, 2014; Marton & Pang, 2006; Marton & Tsui, 2004), comprised of three aspects: (a) the teacher's intended object of learning, (b) the object of the lesson as enacted, which "defines what it is possible to learn in the actual setting" (Marton & Tsui, 2004, p. 4), and (c) the outcome as the students' experienced object of learning. In this way, activity theory provides a way of thinking about the interconnectivity of the teachers' objective—the *planned* curriculum, the students' objective and activity—the *experienced* curriculum, and the realities of the classroom—the complex activity system including the influence of contextual resources (Marsh, 2009). Analyzing the four cases in this chapter by thinking in terms of activity systems, objectives, and resources can also help us more easily compare the enactment and outcome of different lessons, teachers, and materials to answer the research question of how the four lesson criteria afford the testing and revision of design solutions.

Methodology

Study Design

This study focuses on the two engineering design lessons not yet examined by the previous chapters: The Garden Pest lesson enacted in a kindergarten classroom, and the Athletic Shoe lesson enacted in a third-grade classroom. The engineering design challenges integrated with existing curriculum including science standards about human physiology and plant life. The challenges were designed to encourage iteration by providing students with explicit specifications and promoting testing throughout the design process. Students in these two lessons used various craft supplies to construct solutions (including materials like paper, cardboard, tape, straws, fabric, yarn, pipe cleaners, foam, bubble wrap, and chopsticks). The third-grade lessons provided scaffolding for planning in the form of an initial worksheet (see Appendix A), which provided space for a sketch of their planned solution, and questions about how the solution would use the materials to achieve the challenge specification. In the kindergarten classroom, students were not required to plan with pencil and paper before accessing materials. For a more in-depth account of the four lessons, see Chapter 2.

Participants

The research was situated within one kindergarten (ages 5-6) and one third-grade (ages 8-9) classroom in the same elementary school. The kindergarten classroom had 21 students and was facilitated by three teachers (a lead teacher, a teacher assistant, and a student teacher) plus the researcher. The third-grade classroom consisted of students from two classes, 43 students in total, combined for weekly engineering lessons, with the two lead classroom teachers and the researcher facilitating. The three classroom teachers participated in a larger engineering education initiative within the school that provided professional development, material resources, and lesson planning and enactment support from a community of researchers and teacher cohorts. In each classroom, three groups of students were featured in the data collection. These students were selected, with advisement from the classroom teacher, to provide a maximum variation sample of ethnicity, gender, and academic ability. Groups (of two students in kindergarten and three students in third-grade) were formed from the selected students at the teachers' discretion.

Data Collection

I chose to follow three groups within each classroom because I determined that this would provide me with more depth of understanding by documenting the entire process of engineering design rather than capturing fragments of each group in the class. Data were collected in several forms, through notes from direct observation of students within the classroom, photos of artifacts in the classroom, teacher lesson plans, video recordings with a small camera and external microphone at each group's desk (three total in each classroom), and a fourth camera capturing whole-class discussions at the beginning and end of each lesson and otherwise directed at the classroom testing stations when applicable. Through this data, I assembled a holistic view of each group's activity systems, including student practices and interactions with people and artifacts.

Data Analysis

I began my analysis by creating transcripts of the videos, with dialogue and annotation for the students' and teachers' non-verbal actions and manipulation of the materials. I then annotated the transcripts to indicate when students were engaged in evaluating their solutions; this identified episodes not only of formal testing—when students evaluated their solutions at a classroom testing station following the designated protocol from the lesson—but also episodes of informal testing—when students evaluated their solutions through smaller-scale troubleshooting and discussions with their partners at their desks. Through this coding, I was able to locate in the transcripts the students' decisions on how to modify their solutions as a result of testing. As discussed above, it became clear that two lessons, the Garden Pest Lesson and the Athletic Shoe Lesson, did not contain nearly as many instances of students engaging in testing and revision activities when compared to the lessons featured in Chapters 3 and 4.

Narrative Summaries. I compiled narrative summaries (Derry et al., 2010) for each lesson by collecting episodes including testing and revision from the annotated transcripts of the three student groups. Through these narrative accounts, my suspicions from observing the classrooms was confirmed, that some lessons were more productive in promoting iteration than others. Then within each student-group case, I examined episodes in the transcript when students were testing and revising their designs. Within these episodes, I identified the actions and objectives of the teachers and students, and the resources within the context of the classroom related to those activities, including the teachers' lesson planning and enactment. This allowed me to describe the activity systems in the classroom as students were testing and revising their design solutions, and make connections between the students' activity and the mediating factors of the lesson that may have provided affordances or limitations for iteration. It also allowed me to think about the activity system as it related to the *planned curriculum* and *enacted curriculum*, and any systemic tensions which may have been set up between the teachers' and students' objectives. As there is not enough space here to recount the entire work of each group within the course of each lesson, I constructed narratives of the lesson featuring "illustrative examples" as "grounded instances of course activity" (Barab, 2002, p. 86).

Results

The cases presented here are situated within two lessons enacted for this study (see Table 7). These are the two lessons that have not been showcased in previous chapters, and they were chosen for analysis here because the teachers and researchers recognized that these lessons were not affording student iteration. Instead, students were neither critically testing their solutions, nor making revisions to their designs based on analysis. For each case below, I include a narrative summary (Derry et al., 2010) of the student groups' testing activities during the lesson. I also provide illustrative examples (Barab et al., 2002) of episodes of student groups as they engage in testing practices at their desks and at the classroom testing station. For the Garden Pest Lesson, I present two student groups (the third group had a member absent for a significant portion of this lesson); for the Athletic Shoe lesson, I present an illlustrative example of one group, which is representative of the activities observed in the other two groups. After presenting the data, I discuss the implications of the activity system framework on student learning and lesson planning.

Lesson	**Grade-Level**	**Materials**	**Specification**	**Lesson Testing Protocol**
Garden Pests	Kindergarten	Craft	Design something to keep pests out of the strawberry garden while still letting sunlight and water in.	Testing station with garden (basket with fake strawberries), lamp for sun, spray bottle for rain, and small rubber animals for pests.
Athletic Shoes	Third Grade	Craft	Choose a sport, and design a shoe to meet student-specified properties necessary for that sport.	Demonstration at the end of four days to describe properties of show necessary for particular sport.

Table 7. The two lessons presented in this chapter, with materials, specifications, and testing protocols.

Kindergarten: Garden Pests

Students in the kindergarten classroom were given the challenge to design something to keep pests out of their class strawberry garden, while still letting in the light and water plants need to grow. To construct their solutions, students were provided with common craft materials, such as cardboard, pipe cleaners, straws, scissors, tape, and a limited number of wooden chopsticks. The lesson met the criteria that testing be encouraged through a formal classroom testing station, consisting of a small plastic basket containing fake strawberries (the garden), a small rubber mouse to represent the garden pests, a desk lamp to simulate sunlight, and a spray bottle of water to simulate rain (see Figure 21). Students were free to visit the testing station at any time during the lesson, and testing was generally scaffolded by the classroom teacher. This was similar to the testing station and protocol for the earlier Billy Goat lesson.

The teacher planned the lesson to integrate with science standards about plants, and what living things need to survive, and had also read to the class *The Tale of Peter Rabbit*, about a rabbit that gets caught stealing vegetables from a garden. For the lesson criteria that specifications be non-objective and testable, she anticipated that students would choose to build fences or cage-like structures, that would require managing trade-offs in their solutions between gaps that were large enough to let water and light in, but small enough to keep the garden pests out. The teacher did not instruct students to build fences or cages, however, and the lesson criteria that students have some freedom to define aspects of the challenge was met by not dictating the form of the solution ahead of time. Thus, students were not constrained in this way, or in the specifications they might add to their solution (as in the Billy Goat lesson), but they were constrained in the materials available, and in the testing protocol.

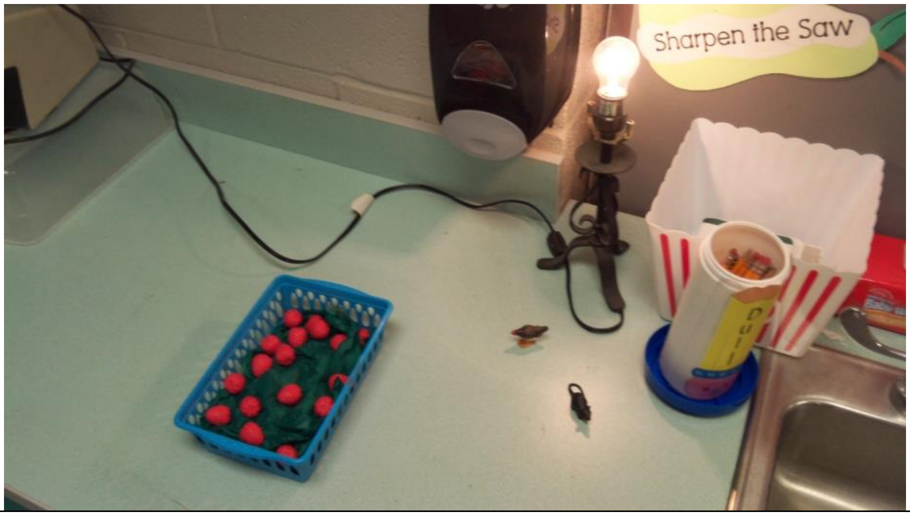


Figure 21.The classroom testing station for the Kindergarten Garden Pest challenge. Shown are the model strawberry garden, the toy pests, and the lamp used to represent sunlight.

In contrast to the Billy Goat lesson, students were initially not concerned with visiting the testing station in order to evaluate their solutions. More generally, they did not seem to connect with the context for the lesson established in the planned curriculum at all, even though it had been introduced through their experiences with the classroom garden, as well as through modeling the environment with toy pests, sunlight, and rain at the testing station. As they built, students spoke only about meeting one half of the challenge: keeping out pests. The requirements for sunlight and water were not mentioned by Abed and D'Andre until after they had visited the testing station on the second day of the lesson, and they were never mentioned by Christopher and Simone. This was despite the teacher reiterating all of the specifications each time she spoke to the class, and emphasizing the need for testing at the testing station, where simulations for light and water were present.

The lesson criteria regarding non-subjective, testable specifications was overshadowed by the freedom and creativity students employed to devise ways to keep the pests from their strawberries. This produced the expected effect on solution diversity, with students proposing designs such as mazes, walls, and physical barriers, along with various "booby traps" (including slides, trampolines, "punchers," "choppers," and falling objects), scarecrows, poisons, and even solutions requiring electricity (electric fences, robots, security cameras). However, the pests that were mentioned often diverged greatly from the context of the testing station (which possessed a mouse and a bird) or *The Tale of Peter Rabbit*. Rabbits and rats were sometimes considered and accounted for in students' design choices, but students also discussed ants, deer, wolverines, tigers, falcons, snakes, and cats in their planning and building. The students' freedom within this lesson did have the consequence of inspiring spontaneous discussion amongst students about animal behaviors and diets, and about whether it was ethical to harm or kill the pests while keeping them out of the garden; one could imagine another incarnation of this lesson taking advantage of this student interest in biodiversity by having groups differentiate their solutions for specific pests, debating humane treatment of pests, etc. Students in the Garden Pest lesson did not challenge their designs as they were building at their desks, merely continually added on to, without assessment as to whether it met the goal of the challenge; there was no tension within the activity system.

Without attention to testable specifications, students were not critical of their designs in a way that forced them to identify areas of weakness necessitating re-design. In the Billy Goat lesson, half of the class initially planned to build vehicles—such as cars, boats, and airplanes—rather than solutions that could be tested for length and strength with the materials at the testing station. Ms. Cook remedied this by announcing that solutions had to be usable by the billy goats themselves, grounding the context of the challenge within the fairy tale and within the testing protocol. Although she did not choose to instruct the students to build bridges explicitly, her modification to the challenge statement served the same purpose, and all students quickly adopted bridge solutions. The Garden Pest lesson offers us a glimpse of what might have been in the Billy Goat lesson, had Ms. Cook not modified the challenge to steer students toward testable specifications. Students in the Garden Pest lesson, instead, gravitated toward solutions that were more fantastical in nature, rather than grounded in the resources inherent in the lesson: the narrative context (either of the classroom garden or *The Tale of Peter Rabbit*) or the context of the testing station (materials or protocol).

The following two cases demonstrate what happened on the second day, when the teacher chose to influence the students' design solutions by guiding them to the testing station when they were not visiting voluntarily to assess their designs.

Case 1: Abed and D'Andre Design a "Booby Trap." Abed and D'Andre had spent one hour constructing an elaborate "booby trap" to keep their strawberry garden safe. The features of this trap had been added, layer upon layer, and addressed several kinds of potential pests. However, many of the traps were contingent upon the animals choosing to enter them, rather than pursuing the strawberries themselves, and the fruit was exposed by gaps in the trap, which sat atop the garden. But while some strawberries were exposed, others were completely hidden under sheets of cardboard, inaccessible to sunlight or watering. The teachers had made several passes by Abed and D'Andre's table during the previous day, asking the boys to explain what they were building, but not critically challenging any of their ideas.

On the second day of building, Ms. Cook ordered that anyone who had not visited the testing station was required to do so as soon as possible. Abed and D'Andre's turn is documented below:

Teacher:	Ok, let's see if [the mouse] can get in. Is he eating any berries yet? [The teacher tries the toy mouse at several openings on the trap.]	Teacher begins testing with pest
Abed:	No. When he comes through here, he will just hit this and get stuck and then the fire will [inaudible].	Student corrects teacher with his vision for what the pest will do.
Teacher:	Uh oh, what's he able to do?	
Abed:	Go crawl under. Just stick his head under. Eat some of the strawberries.	Student acknowledges the pest can eat berries.
Teacher:	Eat some of the strawberries. Now, let's think of this other part. You've got all of these. What are these [strips of cardboard sticking out]?	Teacher and student discuss the path the mouse will take.
Abed:	Um, to hold them. He's going on here...	
Teacher:	So he's supposed to walk on here? [Walks the mouse down the cardboard strip.]	
Abed:	And then...	
Teacher:	He keeps walking.	
Abed:	So, he's going to stop right there.	
Teacher:	But he didn't. He kept on going.	
Abed:	If he thinks...	
Teacher:	But what if he doesn't go in there? What if he doesn't go in there?	
Abed:	Then he will just walk and walk and walk and climb up and climb up.	
Teacher:	But what if he doesn't? He walked to this piece and walked down this piece and still got there and got those strawberries. Now, tell me about these pieces.	
Abed:	If an ant, when the ant comes up, it will just go in here and it will get stuck.	Student introduces ant as pest.
Teacher:	Who will?	
Abed:	An ant.	
Teacher:	But what about this animal [the mouse]?	
Abed:	He just climbs right there [referencing the previous test],	

	Teacher:	Ok, now let's look. Are your strawberries getting a lot of sun?	Teacher begins testing sunlight specification.
	Abed:	Yep.	
	Teacher:	Are they getting a lot of sun, D'Andre?	
	D'Andre:	Yes, ma'am.	Students initially do not agree that sunlight cannot reach the berries.
35	Teacher:	Look at them. Are your strawberries getting sun?	
	Abed:	Yeah.	
	Teacher:	Are *all* of your strawberries getting sun?	
	Abed:	No.	
	Teacher:	No. so are those strawberries going to grow? I need to make sure.	Teacher begins testing water specification.
40		Let's see if my strawberries are going to get watered. Let's see.	
	Abed:	They are.	
	Teacher:	Did *all* the strawberries get watered?	
	Abed:	No.	
The teacher and Abed have a discussion as to whether he could move the traps as needed to allow the strawberries to get sunlight and water. Abed suggests staying up all night, getting a security camera and a large TV to monitor the garden, etc. The teacher rejects these ideas as practical.			
	Teacher:	So does this build keep the animal out from eating strawberries?	Teacher asks students whether design meets all specifications.
45		Does this build give us lots of sunlight? Does this build give us lots of water for our strawberries?	
	Abed:	No.	
	Teacher:	No. So what do you need to go do?	Teacher asks students if they need to revise.
	Abed:	Fix it.	
50	Teacher:	Go revisit, right? And think about how you are going to keep the animals from going around the pieces of your trap.	
	Abed:	Oh, that was bad, but we need to fix it better!	Students agree.

Figure 22. Abed and D'Andre visit the testing station for the first time with their "booby trap" for keeping pests out of their garden.

In this episode, the teacher models the testing protocol, assessing Abed and D'Andre's solution through various simulations of the challenge specifications: pests, light, and water. Abed disputes the test results for the mouse, as his traps rely on the mouse choosing a specific path through the garden (see Figure 22, lines 16-26). Abed may be justified in questioning this portion of the testing protocol, as the behavior of mice is not something one can predict with great accuracy. Ms. Cook does demonstrate, however, that the mouse is able to reach the strawberries through holes in the trap, should it choose to. Regarding the other tests, at first neither boy agrees that their trap does not provide access to light or water for the strawberries to survive (lines 32-38). There is tension between the students' solution and the testing protocol set up by the teacher, not only because the solution is not meeting all of the challenge specifications (this Ms. Cook's focus during the episode), but also because the students seem to reject the testing protocol and its results. It is only when Ms. Cook changes her language to ask if *all* of the strawberries are getting sun and water that the boys acquiesce (lines 37-43). In the end, after some discussion about whether it is possible or practical for Abed to employ security cameras in his design, both students agree that their design needs to be revised according to the results at the testing station (lines 49-52).

The second episode in this case documents Abed and D'Andre's second visit to the testing station. Upon returning to their desks, they did not set to work targeting the results from the first tests' failures, rather they slowly and gradually added and removed features from their solution, until their design was much simpler; the cardboard base and a few remnants of traps remained, but with intentional holes poked in the base that had blocked light and sun before. This time, Abed and D'Andre spontaneously returned to the testing station, at a time when the teacher was away helping another group. The two boys, and a student from another group, immediately set to work assessing the trap to see if the mouse could enter, mimicking the testing protocol followed by the teacher on their previous visit (see Figure 23, lines 1-10). When the teacher arrived, she asked Abed and D'Andre to explain the changes they had made since the previous iteration:

1	Abed:	Look at that. We need to fix up that space [the mouse can fit through].	Student begins testing the mouse while they finished covering holes in the trap.
	D'Andre:	[Adjusting the trap] Abed, stop.	
	Student:	What, a booby trap again?	
5	Abed:	It's awesome, better.	
	Student:	Most of the strawberries aren't getting any sunlight.	Student assesses sunlight specification.
	D'Andre:	[Continues to adjust strips, covering larger holes with foam.]	
	Abed:	[Pecking at exposed strawberry with the mouse.] Peck, peck, peck.	Student continues test.
	D'Andre:	Oh, no, no. We need more of these [foam pieces].	Student requests more material.
10	Teacher:	So, how'd you guys change it?	
	D'Andre:	We made more of these pieces [cardboard strips] to cover it up.	Teacher asks about students' changes.
	Teacher:	How did you change it?	
	D'Andre:	We made more of these pieces, and these [pointing to trap].	
15	Teacher:	Ok. If you cover it up with the foam, are the strawberries going to be able to get sunlight?	Teacher asks about sunlight specification,
	Abed:	Oh, I know. We can make foam. [Explains how to make foam with soap bubbles.]	Students propose revisions.
	Teacher:	But if you cover it with foam, is it going to be able to get sunlight?	
	Abed:	Yes!	
20	D'Andre:	Maybe we could [inaudible] strawberries up, and when it leaves [inaudible] take them off.	
	Student:	Well, if you put 200 dots [holes] in it, yeah.	
	Teacher:	[To D'Andre] But how will you know when it's [inaudible]?	
25	Abed:	There, the sunlight goes through [pointing at a hole in the trap. He tests the hole, to see if the mouse can fit in.]	Student tests a minor adjustment.
	Teacher:	So, Abed and D'Andre, has your build helped solve our problem right now?	Teacher asks if solution has met all the specifications.
	D'Andre:	No, ma'am.	
30	Teacher:	No, ma'am, why not? What about your build has not helped us solve our problem?	
	Abed:	Because it has a lot of cracks [points to holes where mouse can fit in].	Students propose revisions, the teacher scaffolds their thinking.
	Teacher:	It has a lot of cracks, right. Do we need some cracks?	
	D'Andre:	No.	
35	Abed:	Yep!	
	Teacher:	What do we need some cracks for?	
	Abed:	The sunlight, and some water.	
	Teacher:	The sunlight, and some water. And do we need a lot of cracks? Really big cracks?	
40	Abed:	Cracks like that [points to a hole].	
	Teacher:	Oh, so maybe you need something that's small like this? Do you think that will help us get sunlight and some water in?	
	Abed:	Yes.	
45	Teacher:	Yes, ma'am. Ok, so why don't you guys go take your build and think about this kind of crack [points to the small hole] and how you can use this kind of crack on your build.	Teacher asks students to revise at their desks.

Figure 23. Abed and D'Andre visit the testing station a second time. This time they utilize the testing protocol themselves, and attend to all three challenge specifications.

The teacher guided the students through tests to determine whether the strawberries would get sun and light (lines 14-26), employing a strategy of using the students' own language ("cracks") and repeating students' phrases in her responses (line 36, 38). In the end, the tension lay only between their solution and the testing protocol, and they analyzed their revision and planned improvements for the next iteration of their solution based on the results of the testing.

Case 2: Christopher and Simone Build a Scarecrow. Christopher and Simone first designed a scarecrow to deter pests from entering their garden. But when they brought their solution to the classroom testing station, the teacher demonstrated how the scarecrow would not be able to physically stop the pests because he did not cover the whole garden, and could not move without student assistance. It was only with insistence from the teacher that the students agreed to go back to their desk and redesign. As Simone modified the scarecrow to have longer arms, Christopher stated, "We're not making [the scarecrow] again. I'm making a playground so animals will come on it, instead of eating the strawberries." While Christopher accepted the teachers' suggestion that a scarecrow would not meet the specifications for this challenge as presented in the context of the classroom testing station, Simone did not see the problem in persisting with the scarecrow solution. Similar to the case above, Simone experienced a tension between her objective and the validity of the testing protocol to assess her solution. The teacher asked Christopher if he agreed with his partner's choice, and he replied, "I don't know. If it works, yeah; if it doesn't work, no" (see Figure 24, line 19), establishing his acceptance of the lesson's testing protocols.

Simone did revisit the classroom testing station to assess the changes to her design, at the teacher's invitation. She was, however, reluctant to admit that her solution did not meet the challenge specifications to keep pests out (see Figure 24, line 20-21), and the teacher prompted her once again to observe her solution in the context of the testing station (line 24-25), critically evaluate its performance (line 33-35), and remedy (line 59-62) the faults in her solution:

1	Teacher:	What are you working on?	Teacher inquires about solution.
	Simone:	I'm working on a telescope.	
	Teacher:	Why do you need a telescope? How is a telescope going to keep the animals away?	Student rejects that anything is wrong with solution.
5	Simone:	The telescope, [the scarecrow] is going to put it to his eye.	
	Teacher:	But he's not alive.	
	Simone:	I know that.	
	Teacher:	So, how is that going to matter, if the scarecrow's not alive, why does the telescope matter?	
10	Simone:	Because he won't fall asleep, he'll just look out.	
	Teacher:	The telescope won't work because the scarecrow isn't alive.	Teacher asks if student expects solution to work.
	Simone:	But I still want to do that.	
	Teacher:	You want to, but is it going to keep the animals away?	
	Simone:	Yes.	
15	Teacher:	How? Let's go see. Let's go take your scarecrow and your telescope over and see if it keeps them away.	Teacher recommends observation at Testing Station. Partner acknowledges need for observation.
	Christopher:	Can I come?	
	Teacher:	Sure, she's your partner. Do you agree with her telescope?	
	Christopher:	I don't know. If it works, yeah; if it doesn't work, no.	
		At the Testing Station:	
20	Simone:	[Places scarecrow in corner of garden, tries to prop it up by its arms.] I don't know if this is going to work.	Student sets up solution and is skeptical it will work.
	Teacher:	Why not?	
	Simone:	Because.	
25	Teacher:	What do you see? What do you notice happening with your scarecrow?	Teacher scaffolds observation.
	Simone:	I know what's happening is that...[gets scarecrow to sit up on his own].	
30	Teacher:	Ok, he's in there. Alright. Let's see if the animals are going to go in. [Makes mouse eat the strawberry.] The animal can still get the strawberry.	Teacher enacts test, Student rejects that her solution has failed the test.
	Simone:	No, he can't.	
35	Teacher:	The animal is going over and can still get the strawberry. The animal is going in on this side, and guess what? He's still getting the strawberry. So, is what you have helping to keep the animals out of the garden?	Teacher repeats test with same result. Student accepts test.
	Simone:	No.	
	Teacher:	Nope. But what have you noticed? What is this animal doing? He's doing what?	Teacher scaffolds explanation. Student offers variation of
	Simone:	Yeah, if you kicked him out. [Kicks at animal with scarecrow's	

40		leg.]	solution in attempt to pass the test.
	Teacher:	But your hand is doing that. What if you're asleep and your hand's not there?	
	Simone:	Then [the leg] will have to stick out [of the garden].	
	Teacher:	He's still getting in right there.	
45	Simone:	Oh.	
	Teacher:	And he's going behind the scarecrow now and getting another strawberry. And look, he's getting this one. This animal is getting all these strawberries. Is your scarecrow keeping the animal away from getting any of the strawberries?	Teacher repeats scaffolding of test results and explanation.
50	Simone:	No.	
	Teacher:	So, do you even need [the telescope]? Is that going to help you?	
	Simone:	No.	
	Teacher:	So, what can you do to keep the animals from getting any of the strawberries?	Teacher ask student how they can revise. Student offers another variation of current solution in attempt to pass test.
55	Simone:	I can change it.	
	Teacher:	What are you going to change it into? What can help keep the animal from getting into, look at how the animal is getting into it.	
	Simone:	Um, just poke [the leg] out.	
60	Teacher:	He's still getting in. He's going in on this side, on this side. He's still going in on this side.	Teacher repeats scaffolding of test and prompts student to revise at desk with her partner.
	Simone:	I'll make a...	
	Teacher:	Go talk to Christopher about it. I think that's very important.	
	Simone:	[As she returns to her desk.] I did it! I kept the mouse out!	Student asserts that her solution passed the testing, but her Partner asks for proof.
	Christopher:	You did? Show me!	
65	Simone:	You put it like this, and this thing [the arms] sticks out all the holes and it did it!	
	Christopher:	Let's go see with the teacher and see if it did.	
	Simone:	I can't, I have to do it one more time. I'm going to make another thing.	Student's revision is a new solution.
70	Christopher:	What?	
	Simone:	I'm going to make something that's easier. I'm making something the animals are going to eat.	

Figure 24. Christopher and Simone engage in an informal discussion about their solution with the teacher, who then leads them to formally test their design at the classroom testing station.

Instead of using the scarecrow as a deterrent for pests entering the garden, Simone intended for the scarecrow to physically keep the pests out, which of course cannot happen without some means of moving the scarecrow. Despite her solution's failures at the testing station, when Simone returned to the table, she claimed that her design was successful; Christopher was skeptical and asked for proof (lines 64, and 67). Abandoning the scarecrow design, she announced she was going to "make something that's easier" (line 71). Christopher went on to test his new design at the classroom testing station, and after he returned, articulated the testing protocol and his plans for revision by summarizing for Simone, "It didn't work very good. The animals jumped over it. So I'm going to make this thing way bigger."

Lesson Criteria and Affordances for Iteration. The episodes above show that the students observed eventually applied results from the testing station to inform the revision of their designs, but only after significant interaction on the part of the teacher. In the case of Abed, D'Andre, and Simone, the initial tension encountered in the activity system was not between the performance of the solution against the testing protocol, but rather challenging the validity of the testing protocol at all. These tensions were eventually resolved, however after these episodes, even after revising, students did not return to the testing station before running out of time. At the end of the second class-period, none of the student groups I observed had constructed a solution which had passed the testing protocol. The degree of iteration anticipated by the teacher when developing the planned curriculum was not realized in the enacted curriculum. In what ways was iteration afforded or limited by the four lesson constraints which were theorized to promote iteration?

Two of the criteria dealt with not "over-constraining" the challenge, and allowing students to "have a role in defining the problem." This lesson allowed freedom for students in deciding the design for their solution. In the planned curriculum, the teacher anticipated that students' solutions should take the form of fences to protect the strawberries, but did not specify this design in her instructions. As a result, there was a great diversity of design solutions around the classroom. The argument for not over-constraining the challenge was to allow for students to have many options to fall back on if their first design failed. On the extreme end of this spectrum, over-constraining an engineering design challenge can turn an activity into following directions to build identical solutions, which will not engage learners either in generating a solution or analyzing and revising it. Ignoring the context for the challenge established by the testing station or classroom garden narrative, students took more of a role in defining the challenge than was intended. They added a variety of pests to the design specifications beyond the rabbits, mice, and birds discussed in class, and envisioned solutions which used materials not available to them—most notably the means to create movable scarecrows, cameras with television monitors, or poisons. The students' objective of designing an elaborate deterrent for the animals, and the teacher's objective of promoting a design to meet the pest specifications as represented at the testing station, as well as the water and sunlight specifications, were not well aligned with each other. While this degree of student freedom does afford teachers the opportunity to shape the lesson to accommodate student thinking, (incorporating ethics, for example) in these cases it did not provide affordances for students to revise their solutions.

The other two lesson criteria for iteration related to testing were that the challenge have "definable and non-subjective specifications," and that "testing and re-design are explicitly encouraged by the structure of the lesson and classroom." Teacher designed three specifications, pest, sunlight, and water. These were meant to have trade offs with space small enough to keep pests out but large enough to admit water and light. As envisioned by the planned curriculum, success for the pest specification was tied to hole size, not animal behavior. Student introduction of solutions like traps made it necessary for the teacher to introduce the "choices" mice would make when traversing solutions in the testing protocol, which gave the students an opportunity to reject the way the teacher was modeling the pest's behavior in favor of how they predicted the animal would act. The students shifted what was originally an objective specification toward a more subjective, less-testable one. Animal behavior is a more subjective constraint than evaluating whether sunlight and water are reaching the plants, and yet students were also reluctant to admit that their solutions did not meet those specifications as well. Alone, these non-subjective specifications did not afford iteration.

The teacher's planned curriculum was mediated heavily through the use of the testing station, including the testing protocol, materials, and teacher scaffolding. Having the physical representations of the size of the pests (the toy mice), the sun (lamp), and rain (spray bottle) was anticipated to provide affordances for the students' consideration of these specifications in their solutions. Through scaffolding from the teacher and classroom testing stations, students were prompted for observations as to whether their design was successful. A tension was observed as students struggled at first to recognize why their solution was failing a test, or did not accept that it was failing at all. Both the students' objective and the teacher's objective for this lesson included designing a solution to protect a garden from pests. However, the solutions students initially brought to the testing station were a poor match for the testing protocol established by the lesson, with elements that were more representational rather than functional, and largely ignoring the specifications regarding sunlight and rain, indicating that the students' experienced curriculum was not aligned with the teacher's planned curriculum.

Upon their first visit, students seemed in opposition to the results from the testing station, as scaffolded by the teacher. After returning to their desks (for the second time, in Simone's case), the students acknowledged the need to revise in order to meet the challenge specifications as modeled by the testing station. Abed and D'Andre eventually showed confidence in testing their solution independently, without teacher scaffolding. Well-defined, non-subjective testing (such as the mouse-size test intended by the lesson, more so than the mouse-behavior test necessitated by the students' trap design) provided the biggest affordances for evaluating and revising their solutions to improve test results. The teachers' scaffolding did encourage the students to increase their participation in the classroom practice of testing as defined by the lesson; by the end of the lesson, none of the student groups had a solution which met all three specifications, but using feedback from the testing station, they recognized the need to revise their solutions accordingly. Despite this, students still did not test frequently, and the necessity to end the lesson due to classroom time constraints might have been an issue. The indifference students exhibited toward visiting the testing station was a symptom of the lesson being under-constrained, and students having freedom to stray away from the context inherent in the testing station itself.

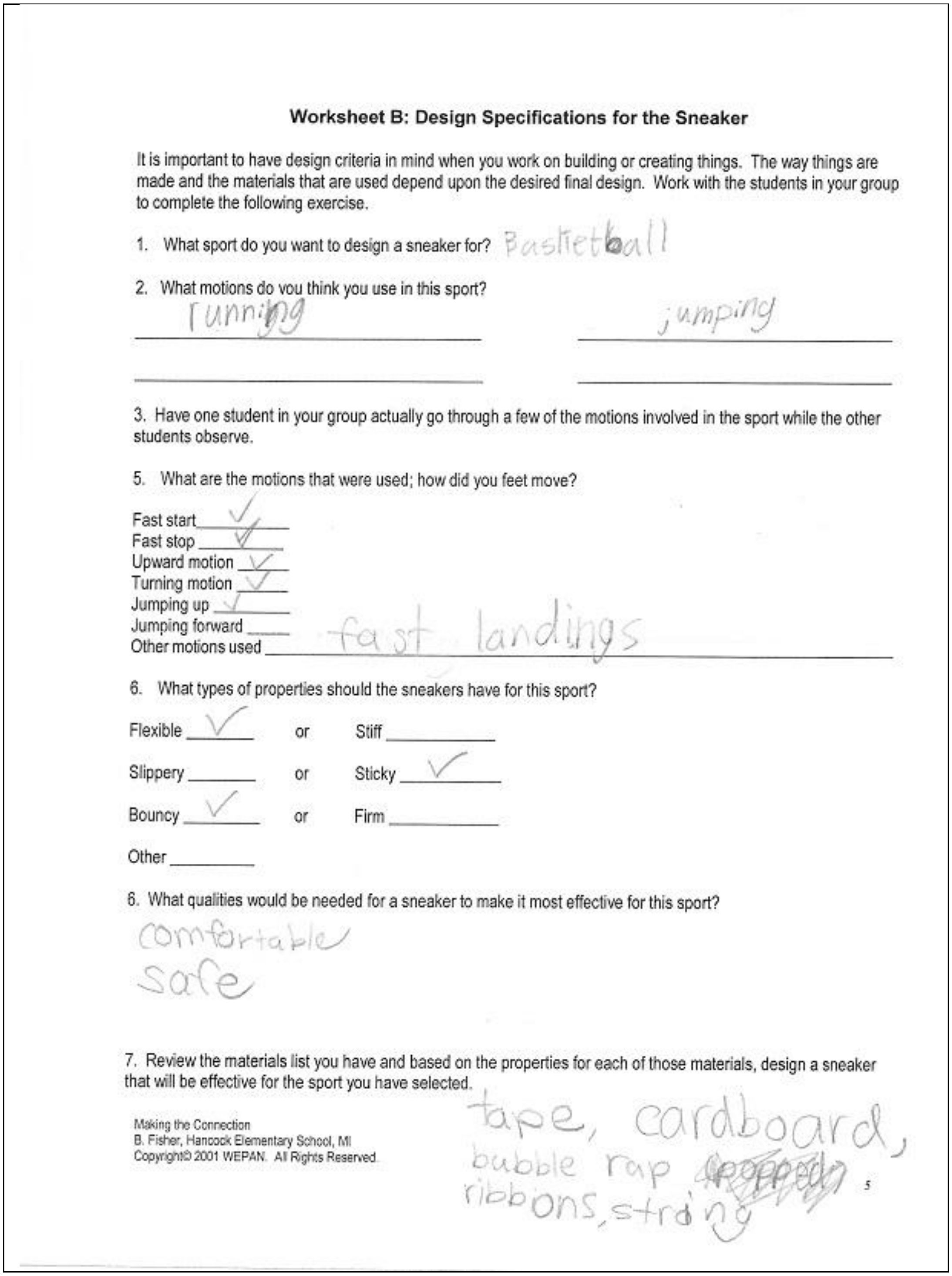
Third Grade: Athletic Shoes

In this lesson, students in the third-grade classroom received the challenge to design an athletic shoe for the sport of their choice. To construct their solutions, students were given household materials, such as cardboard, bubble wrap, foam disks and peanuts, fabric, ribbon, coffee filters, and tape. The specifications of each shoe were left up to the groups to define for their particular sport. Students did have the aid of an initial planning worksheet (see Figure 26), which asked them to identify the physical motions necessary to play their sport, and the resultant properties the shoe would have to possess, with a few suggestions, such as "fast start" or "jumping up," and "flexible or stiff" or "bouncy or firm." There was also space for them to list the materials they planned to use, and a large sheet of paper to sketch their ideas. This lesson did not feature a classroom testing station, nor any guidelines or rubrics for testing, but students did participate in a "fashion show" at the end of the fourth day to showcase their design. On the first day, students learned about the physiology of the human foot and how shoes are commercially made. The second day was generally spent planning, while during the third and fourth days students were free to plan, build, and evaluate at their own pace.

The Athletic Shoe lesson was based on a unit the third-grade teachers had used in previous years; this enactment was informed by the four criteria for promoting iteration. Students were given a role in defining the challenge through their choice of sport, and the identification of what characteristics their shoe should have. During the planning phase, many students made reference to their experiences playing sports, and their own athletic shoes, as they designed their solutions. The planning worksheet was ostensibly supposed to provide students with testable, non-subjective specifications for their athletic shoes. The lesson was not over-constrained, but neither were portions of it sufficiently scaffolded. While the planning worksheet guided students in the identification of the shoe's required properties, students were given no assistance in defining what properties such as "slippery" meant, or how to test whether a shoe was "slippery" or not. Students attributed some of the properties of their shoes to their chosen construction materials, but more often materials were selected for their functional abilities, or their resemblance to components in an actual shoe. Students did observe the performance of their shoes, but instead of properties necessary for sports, students focused universally on comfort (see Figure 25 for examples of the shoes). Group members asked the shoe wearer to assess the shoe's comfort at various stages throughout building, and students reasoned about the best materials, making improvements when problems arose, continuing until the last day and the fashion show. The lack of scaffolding for testing the specifications might have been remedied by including a formal testing station, as seen in the other three lessons comprising this research study. Instead, students were tasked with describing the specifications for their athletic shoes during the fashion show, and how the properties of their show met these design requirements.

Figure 25**.** Third-grade students at work constructing a comfortable sole for their shoe (left) and an outer covering to keep the shoe on the foot (right).

Case 3: Shoes for Basketball. Cameron, Jordan, and Kayla had chosen to design shoes for playing basketball. On their planning worksheet (see Figure 26) they identified that the sport would require running and jumping, the motions feet would undergo playing the sport, and the properties required for the shoes themselves ("flexible," "sticky," and "bouncy"), and other qualities of athletic shoes, including "comfort" and "safe[ty]." They made a cursory sketch of the shoe, but most of their planning took the form of discussion and debate. They selected materials specifically with different parts of the shoe in mind: cardboard to be strong for the sole, bubble wrap to be comfortable for padding, with ribbons and string—both decorative and functional—as the upper. The students did not refer back to the planning worksheet often after completing it on



Worksheet B: Design Specifications for the Sneaker

It is important to have design criteria in mind when you work on building or creating things. The way things are made and the materials that are used depend upon the desired final design. Work with the students in your group to complete the following exercise.

1. What sport do you want to design a sneaker for? Basketball

2. What motions do you think you use in this sport?

running   jumping

3. Have one student in your group actually go through a few of the motions involved in the sport while the other students observe.

5. What are the motions that were used; how did you feet move?

Fast start ✓
Fast stop ✓
Upward motion ✓
Turning motion ✓
Jumping up ✓
Jumping forward
Other motions used fast landings

6. What types of properties should the sneakers have for this sport?

Flexible ✓ or Stiff
Slippery or Sticky ✓
Bouncy ✓ or Firm
Other

6. What qualities would be needed for a sneaker to make it most effective for this sport?

comfortable
safe

7. Review the materials list you have and based on the properties for each of those materials, design a sneaker that will be effective for the sport you have selected.

tape, cardboard,
bubble rap ~~popped~~
ribbons, string

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Figure 26. Planning worksheet used by Cameron, Jordan, and Kayla when designing their basketball shoes.

the second day, or discuss the specifications (flexibility, grip, and bounce) generated by that document. Overall, the shoes did not go through cycles of testing and revision, but were incrementally built up, from sole to upper, evolving as students negotiated with the materials and each other, and only addressing issues related to comfort or fit.

As they built, Cameron, Jordan, and Kayla engaged in troubleshooting small problems that interfered with their construction goals. One such problem is illustrated in the transcript below (see Figure 27) where the materials the group has chosen for the padding (bubble wrap and cotton balls) were not behaving as they desired (lines 2-5):

Jordan:	[Tries on shoe.]	Observation
Cameron:	Stop popping [the bubble wrap].	Suggestion of what is not working well.
Jordan:	I'm not, it's my weight.	
Cameron:	The cotton [ball] is falling out.	
Jordan:	See?	
Cameron:	We need to take [the sole] apart.	Fix for the problem.
Jordan:	Yeah, of course.	
Teacher 1:	[To whole class] Ok, who has a prototype? That means you have something that you're almost done. Like, you can wear it, you can kind of see how it works. Alright, you need to test out your prototype to see what happens. Over here, Priya said she was very uncomfortable while she was wearing it. So is this shoe complete? [Class: No, ma'am.] So what do we need to do? Make it more comfortable. They need to fix that problem, so they need to look back and recreate, or look at that area that is failing that is not meeting the needs of the shoe wearer and improve it. So make sure, those of you that are wearing the shoe, let people know how it works. If it's falling off your foot, then that's not good either, right? So, about 15-20 more minutes to continually improve.	Teacher makes announcement to class about testing the shoes, specifically for comfort and whether it stays on the foot.
Teacher 2:	So, what are you guys doing?	Teacher asks for observation. Students explain how they have designed for comfort and to stay on the wearer's foot.
Cameron:	We're making the shoe more comfortable on the bottom.	
Teacher 2:	Ok, so what's the bottom or the top?	
Cameron:	This green part. That will make it more cushiony.	
Teacher 2:	And how is somebody-- who's wearing this?	
Cameron:	Jordan.	
Teacher 2:	Ok, Jordan, how is it going to stay connected to your foot?	
Cameron:	We were going to tape it to his sock.	
Teacher 2:	So, every time, like think about in real life, though. How would he like it, if that was really a shoe?	Teacher scaffolds observations and explanation of their
Jordan:	I was just talking about putting the side on, but they said not...	

Cameron:	We could do the sides.	design.
Teacher 2:	But you should think about that, because if I had to, every time I put my shoe and I had to glue it or tape it to my sock, first of all, I'd be worried it might fall off. Second of all, that doesn't seem like the most realistic thing. So think about how you can, and what you should do. Ok?	
Kayla:	I keep telling them to put that, like, a little corner. We can get a coffee filter, put it right here. Um, put it at the beginning of the shoe, just cut it in half, put it right here so it can have it like that.	Student suggests a remedy.
Cameron:	Yeah, Jordan, we need you to get the coffee [filter].	

Figure 27. Cameron, Jordan, and Kayla evaluate the comfort of their shoe, and with teacher prompting, assess the fit of their shoe as well, and subsequently revise the solution.

While this episode demonstrates that students were critiquing designs and modifying their solutions accordingly, they were not doing so on a very critical level, and with only one specification out of the five originally identified. Such issues with materials were easily explained and remedied by adding more bubble wrap, or an additional strap, with no further evaluation of the solution's performance (lines 21-23, 27, 37-40). Within the activity system, the only tensions observed were in how the students would use materials to realize their solutions, which did not lead to critically evaluating or revising their designs.

This lesson did not feature a testing station, as the other three in this study had, so interactions between the teacher and students regarding their solution occurred at the groups' tables as the groups were building, rather than while scaffolding a testing protocol. Near the end of the last day, Ms. Lyons announced to the class that they should be testing their prototype before the final fashion show, suggesting, for example, that they should ensure the shoes would stay on the wearer's foot. This explanation, followed immediately by a discussion with Ms. Bastille on the same topic, lead to this group addressing the additional specification of fit, alongside comfort, in their solution (see Figure 27, line 26-

40). The other specifications from the planning worksheet were never mentioned by the teachers. The lack of a testing protocol meant students were relying on the materials and teacher to guide the evaluation of their solutions. But even this teacher-interaction within the activity system did not establish tension related to original, planned characteristics of the athletic shoes and instead focused on issues such as comfort.

During the end-of-lesson fashion show, students shared the necessary properties they had identified for their chosen sport as they demonstrated their shoes (see Figure 28). However, students were never asked to demonstrate how their shoes met these specifications, such as firmness or flexibility, or defend their material or construction choices in a non-subjective way (lines 1-10). The notion of a "fashion show" fails to focus on athletic specifications and instead implies a demonstration of form over function. During the presentations, each group responded to a question from another student, which generally focused on comfort (line 12). With the absence of a classroom testing station or protocol for testing the properties of shoes, the two groups' solutions were never critically evaluated (lines 9, 15-16). The final product was the result of what would functionally work to keep the shoe on the student's foot, with some padding at the bottom for comfort, rather than the specifications scaffolded by the planning worksheet, and the solutions did not undertake extensive redesign from the outset of the challenge.

Teacher:	Tell us about the shoe. Who is the shoe for?	
Cameron:	This shoe is for beach basketball. The motions that it would use is running, jumping, and faking out. The motions used are upward, turning, jumping, jumping forward, and backward. Properties that the prototype – the things that it would need to make it able to be basketball shoes – flexibility, slippery, and bouncy. We used cardboard, tape, fabric, peanut fuzz [packing peanuts], cotton, coffee filter, and we didn't use string and ribbon.	Student lists qualities without justifying or demonstrating them. Some of these qualities were not present on, or conflict with, planning worksheet.
Teacher:	Great! Excellent! Round of applause [clapping]. Can you pick someone for a question or comment?	Teacher tells student to ask for feedback.
Kayla:	You, Liam.	Other student asks question about comfort.
Liam:	What did you put comfortable in it? Or can it move?	
Cameron:	It should be comfortable because we put a lot of peanut fuzz and bubble wrap inside of it so it should be able to be comfortable.	Student justification based on materials.
Teacher:	I love the way you say it's comfortable because of this. Great job! Yeah, excellent.	Teacher affirms without student demonstration.

Figure 28. Cameron, Jordan and Kayla demonstrate their shoe for the class during the "fashion show."

Lesson Criteria and Affordances for Iteration. The episodes above show that the students observed were able to choose a sport, consider the required motions of the foot for that sport (an integration of the science curriculum), and then generate many characteristics of athletic shoes that could have served as specifications for their design. However, attention to these specifications was not scaffolded beyond planning, and interactions with the teachers and materials guided students instead to attend to comfort and fit. As a result, the students did not go through iterative cycles of testing and revision, but rather gradually built up their solutions while troubleshooting problems with the materials. In what ways was iteration afforded or limited by the four lesson constraints which were theorized to promote iteration?

Students did engage in some assessment of their solutions at their desks, but only for specifications like comfort and fit. There was no established testing protocol, or otherwise a way for students to define success or failure for the athletic criteria. Iteration was not afforded by the materials available for the challenge, or by the discussions students engaged in with their teachers, insomuch as the teachers only addressed the specifications of comfort and fit as well. Other specifications identified by students during planning were not addressed at all through the building and revising process, and referenced only during the fashion show, with no evidence of their success. The fashion show did not serve to replace a testing station in terms of ensuring that students will assess their solutions for all of the specifications intended, preferencing fit and comfort. Additionally, its location at the end of the lesson does not afford iteration, and instead reinforces the one-pass model of engineering design challenges.

The specifications identified by students during planning were conceivably testable requirements and not altogether subjective. Comfort, however, is highly subjective, and fit only slightly less so. With guidance from the teachers, students could have devised appropriate tests for the flexibility, grip, and bounce of their solutions, but this was not part of the planned curriculum. Students did not attend to these constraints while building their athletic shoes, but even if they had, without a definition of success for these specifications, they likely would not have turned a critical eye toward their designs.

In comparison to the other third-grade lesson, students spontaneously and frequently tested in the Marshmallow Thrower lesson because there was one specification and it was easy to assess success or failure. The Athletic Shoe lesson, while not as ill-defined as the Marshmallow Thrower, was not over-constrained, but does that matter for promoting iteration? Student freedom to pick a sport, and define the properties of shoes, afforded student engagement through connections to their own experiences, but it was unutilized as an affordance for iteration in the planned and enacted curriculum. Likewise, diverse materials led to typical shoe construction (cardboard for soles, soft things for cushioning and comfort, etc.), reinforcing fit and comfort, but not necessarily the other planned specifications. The role of students in this challenge was intended to integrate with science topics in human anatomy, but due to the structure of the lesson, even this was not afforded beyond the first day's observation of feet and the planning worksheet.

While students nominally completed the planning worksheet which scaffolded their thinking about the properties of athletic shoes, these specifications were not subsequently important in the creation and revision of their solutions. First, students prioritized comfort, fit, and material management over the athletic specifications. Second, any conceptions students had about what properties were necessary for athletic shoes were unchallenged by the lack of a rigorous, non-subjective testing protocol, and thus assumptions about the performance of their shoes (flexibility, grip and bounce) were allowed to persist and solutions remained unrevised. This fact is neither recognized nor challenged by the teachers during the enacted curriculum, and absent in the experienced curriculum. Unlike the first case, where students were reluctant to engage in, or accept the results of, the testing protocol, students in this case did evaluate their shoes, but not rigorously, or for the specifications intended by the teachers in the planned curriculum. The practice of testing students exhibited in this classroom reflected the students' experienced curriculum because the resources in the planned curriculum did not provide enough affordances for iteration.

Discussion

In my research question, I asked: how do the four lesson criteria introduced in Chapter 2 influence the students' iterative activities of testing and revision? To answer this question, I examined the lessons that had been deemed not as successful in promoting iteration, with the expectation that it would allow me to also observe instances when these criteria were not affording iteration. I identified areas where the teacher's objective for the lesson—the *planned* curricula—did not result in the expected student activity of testing and iteration.

One criteria for promoting iteration was that lessons are not "over-constrained." For young elementary students, not over constraining the challenge did result in creative, diverse solutions. But these students lack the expertise to rigorously evaluate these solutions to the extent that they are iteratively improved without sufficient scaffolding in defining success for their solutions. In their *Informed Design Teaching and Learning Matrix*, Crismond and Adams (2012) suggest that beginning designers hold tenaciously onto their design ideas even after testing uncovers flaws, leaving them barely changed despite numerous iterative cycles; their evaluation of design solutions is uncritical, coarse-grained, and unfocused; and they see a design as satisfactory, where a more experienced designer would recognize flaws. While experienced designers run valid investigations that help them understand how their design works and diagnose problems, Crismond and Adams (2012) claim that beginning designers run few to no tests on their design prototypes. It could be that young students frequently require guidance in order to understand the tensions between the testing protocol and their design solution; instead of attempting to shift their design by evaluating and revising it, they instead push back against the protocol itself.

Encouragement of frequent testing was another lesson criteria for promoting iteration. As suggested by Crismond and Adams (2012) above, if students do not look for, or recognize, the ways in which their solutions fall short of the required specifications, and their attention to evaluation is unfocused or not critical, there is no impetus for the iterative improvement of their design. However, with scaffolding on the part of the teacher, a testing protocol can be adopted by the students, what Kolodner (2006; 2003) recommends as a ritualizing practice to construct a classroom culture of testing. In the Garden Pest lesson, the solutions devised by the students did not make use of the lesson context and testing protocol devised by the teacher, and resulted in solutions which did not lend themselves to testing at the classroom testing station. This was only overcome through extensive scaffolding at the testing station, as at first, students rejected not only the need to test, but also the evaluation conducted at the testing station. Without making a judgment as to whether this was the appropriate course, or whether the teacher should have accommodated the students' understanding of the challenge context instead, it did result in increased participation of students in applying the constraints of the testing station to their designs, and in responding to testing with suggestions for revision. During the Billy Goat lesson students were already participating in testing the relevant constraints at their desks before visiting the classroom testing station. However, the testing protocol provided affordances for the students to recognize flaws in their solutions, and thus promoted productive revision of their designs. In the kindergarten classroom in general, the interaction with the teacher and the testing materials at the testing station provided affordances for promoting participation in critical evaluation of solutions, and revisions that led to improved performance.

Another criterion for promoting iteration was the presence of testable, non-subjective specification, a criterion that was synergistic to the encouragement of testing. In the third-grade Athletic Shoe lesson, the initial planning worksheet afforded students' identification of many legitimate specifications for shoes tailored to their chosen sport. The planning worksheet and final fashion show of the Athletic Shoe lesson were intended to provide affordances for attending to these specifications, but fell short as experienced curriculum in that there were no affordances for iteration in between. The absence of a well-defined testing protocol did not preclude students evaluating their solutions throughout construction, however, the students' testing did not focus only on comfort and fit, not on the specifications intended by the teachers in their planned curriculum. In the Garden Pest lesson above, students become more conscious of specifications they had ignored in their solution through interactions with the teacher and testing protocol at the formal testing station. In the Athletic Shoe lesson, there were no critical tests of the shoes' performances to afford student consideration of these specifications, so the solutions themselves were not critically challenged or revised beyond functionality and subjective comfort.

The last criteria involved providing students with a role in defining the problem. The Marshmallow Thrower lesson, detailed in Chapter 4 framed as a competition, offered affordances for students to test and revise aggressively and utilize the mathematical standards of measurement and graphing, in order to attempt to claim first place. Thus, participation in the practice of testing, and revising the design for better performance was necessary for achieving the students' objective of winning the challenge. Although students were able to define many aspects of the Athletic Shoe challenge, such as the sport they would design shoes for, and personally related the challenge to their own experiences, this did not prevail over the lack of affordances for assessing the athletic-related specifications. Similarly, students in the Garden Pest lesson overlooked the challenge connection to their classroom strawberry garden, and instead focused on solutions which were not practical given that context.

Conclusion

This chapter examined two engineering design lessons, specifically focusing on the student practice of testing, and the subsequent revision of their solutions. Using activity theory as a framework, I argued that each of four lesson criteria for iteration, detailed in Chapter 2, provided affordances for iteration to a greater or lesser extent. There are two major findings from this chapter. In order to promote iterative practices, it has to be clear how students should test non-subjective (and subjective, if applicable) constraints. This follows the students being able to identify constraints (see also Chapter 3). Also, students need to be able to define what successfully fulfilling each of the specifications might look like. Tests are of little value if students cannot determine whether their solutions have passed or failed, since my observations show students will not tend to revise a solution if there is no discrepancy between the solution and the test results.

This has implications for the design of engineering education curriculum and the promotion of student participation in the classroom. When planning and enacting engineering design challenges to promote iteration, teachers should first and foremost promote testing of non-subjective specifications. These specifications can be defined by the students, giving them a greater role in the challenge; however, it is important to help the student define success for each specification, in order to ensure the solutions are addressing each specification. In most cases, where specifications are shared throughout the whole classroom, a classroom testing station is one way to provide students with a means to assess their solution against a standard testing protocol, and allows teachers to scaffold student analysis and revision to whatever degree necessary. This provides affordances that encourages students to recognize flaws in their solutions, and motivate them to improve the solution accordingly. Enabling students to have degrees of freedom within the challenge to define their own role or characteristics of their solution may also promote iteration, but this lesson criteria is difficult to enact; this study identified many opportunities for teachers to differentiate lessons toward student goals and interests, but did not have the data necessary to assess the impact on affording iteration. For the youngest students, there appears to be a trade-off between allowing for more student freedom resulting in creativity or diversity of design solutions, and constraining the challenge and context such that the designs are more homogenous, but promote objective testing and critical analysis.

Chapter 6. Conclusion: Implications and Future Steps

In this dissertation, I examined the student practice of iterative design in the context of engineering design lessons within early elementary classrooms. In a collection of three empirical chapters (Chapter 3, 4, and 5), I employed a theoretical perspective influenced by aspects of situative cognition and activity theory to explain shifts in student activity and objective as they attended to design constraints, engaged in testing, and followed iterative cycles of revision. In this chapter, I reflect on both the theoretical implications of this dissertation—for the body of engineering education research—and the practical implications—for classroom implementation of engineering education at the early-elementary level. I also discuss the limitations of this study, and propose future avenues of research.

Reflections and Implications

Theoretical Contribution

Mitchel Resnick (2007) has written about the potential benefits of taking a "kindergarten approach to learning" at all grade levels. He argues that this approach, characterized by a spiraling cycle of Imagine, Create, Play, Share, and Reflect, is ideally suited to meeting the educational needs of the 21st century. He notes that the last step, Reflect, is critical to the creative process, but is frequently absent in classrooms:

> In recent years, schools have adopted more "hands-on" design activities, but the focus is usually on the creation of an artifact rather than critical reflection on the ideas that guided the design, or strategies for refining and

> improving the design, or connections to underlying scientific concepts or related real-world phenomena. (Resnick, 2007, p. 5)

One cannot help but notice the obvious similarities between the kindergarten approach and the traditional engineering design process. Resnick (2007) similarly esteems the concept of iteration, continuing:

> It doesn't matter whether they are creating an animated story or building an interactive sculpture. In all cases, our message is the same: iterate, iterate, and iterate again. Time, of course, is essential in this process. If children have enough time to go through the cycle only once, they'll miss out on the most important part of the creative process (p. 5).

The iterative nature of engineering, and these reflective practices of testing, critiquing, improving, and connecting to outside material, are exactly the things happening in elementary engineering classrooms, on which I hoped my research would shed light.

Resnick's implicit thesis seems to be that, given the proper materials and guidance, kindergartners are natural engineers. However, when we look at the engineering education research, what few sources we have seem to suggest that the activities undertaken by young students are far from the practice of professional engineers. Crismond and Adams (2012), in their *Informed Design Teaching and Learning Matrix* assert that among other behaviors, beginning designers:

1. "Do few or no tests on prototypes, or run confounded tests" (p. 749);

2. "Design in haphazard ways where little to no learning gets done, or do design steps once in linear order" (p. 749); and
3. "Treat design tasks as a well-defined, straightforward problem that they prematurely attempt to solve" (p. 748).

These conclusions are based almost exclusively on research with students in the secondary grades and university level. Despite the consensus of the existing literature, my three studies reveal that young designers exhibit many activities akin to the practice of professional engineers—such as rigorous testing of solutions, bottom-up design, and attention to complex constraints—within the context of the classroom.

In Chapter 3, I examined kindergarten students' attention to constraints as they constructed and iterated upon design solutions, suggesting that students consider not only the *explicit constraints* (specifications) detailed in the initial challenge, but also the *emergent constraints* derived by the students themselves, implicit in the context of the classroom. The teachers designed the lesson to be fairly straightforward, with only length and strength as specifications. However, students responded to certain affordances and limitations within the classroom environment that influenced their attention to constraints on their solutions. The students' introduction of emergent constraints indicates that they were comfortable defining their own constraints, and thus did not view the challenge as presented by the teacher as a straightforward, well-defined problem. If students attempted to construct a complete solution earlier in the process than an experienced designer would, they were also very responsive to the affordances of the testing station for identifying and improving failures in their designs. As students iterated, *explicit constraints* tended to be more influential in shaping their design because the testing stations and protocols established by the teacher set up systemic tensions between the students' solutions and those constraints of *strength* and *length*. This chapter informs our understanding of how young students iterate because attention to constraints are essential to evaluating design solutions.

In Chapter 4, I confirmed that third-grade groups' activities can follow a traditional, plan-driven approach, with the objective identifying deficits in the design and correction them, but also that an experimentation-driven, process, with the objective of optimizing through inquiry of variables. While the former is privileged in classrooms and engineering curriculum, the latter, often referred to as tinkering, is both successful in creating functional solutions, and helpful in building domain knowledge for novices who might not possess enough experience with engineering concepts or materials to pre-plan a successful design. Through both approaches, students engaged in similar engineering practices of reflection and testing in highly productive ways, while gaining knowledge and constructing functional solutions. This chapter provides evidence that young students can handle complexities in challenges and iterate upon solutions via diverse processes, just as experts do.

In Chapter 5, I analyzed how the four lesson criteria in Chapter 2 could provide affordances for iteration. Iteration is afforded by lessons where students are engaged in testing and revision, I was able to identify affordances provided by resources within the classroom environment, namely well-defined testing protocols performed at formal testing stations, along with teacher scaffolding for devising and testing specifications. Students' designs did not undergo much revision when the systemic tensions in the activity system were challenging the testing protocol rather than challenging the design solution itself. Contrary to the proposed lesson criteria, young students often required strategic constraining of problems in order to keep students in the appropriate context for the challenge and to produce solutions which are testable, however students handled the ill-defined challenges well in other ways, such as when they proposed additional constraints for their design. Giving students a role in defining the problem increased motivation, but did not afford iteration without the teacher scaffolding to help bring them into the classroom context. Thus, we can conclude that kindergarten and third-grade students given resources with the proper affordances, are capable of participating in the practice of critical testing and revision. This chapter informs our understanding of how young students iterate by highlighting the influence of an activity system and mediation of resources on a students' decision to revise their design.

Essentially, I disagree with Crismond and Adams' (2012) decision to lump all novice students, young and old, K-16, together as beginning designers. If researchers, curriculum developers, and teachers underestimate early-elementary students' capabilities with respect to engineering design behaviors, it is because they attempt to compare young students to adults, when they are clearly very different. We expect behaviors from high school or college students that early-elementary students are not developmentally capable of, such as metacognition, or experientially capable of, such as planning without domain-specific knowledge. If we hold kindergarten and third-grade students to professional standards, they will fall short. However, we are not asking kindergarteners to build highway bridges and artificial limbs—yet. If we focus on practice rather than product, and instead explore the processes these students employ within the classroom rather than real-world context, we can see many complex behaviors that, with proper scaffolding and support, will develop into productive adult engineering behaviors.

Pedagogical Contributions

Katehi et al. (2009) claim that the field is missing pedagogical implications that are based on empirical research. Thus, part of the goal of this dissertation was also to look at students within the context of the classroom, describing through activity theory how the lessons, materials, interactions, and objectives shape engineering design activities. The students in this research project were operating within extremely open-ended, ill-structured environments compared to many elementary engineering lessons and curricula. This makes the students' design behavior even more exciting, because instead of following a model engineering design process step-by-step, they were iterating upon their solution when it was appropriate to their particular needs, and at varying grain sizes, from troubleshooting the solution at their desks, to incremental improvements regarding one constraint, to large-scale overhauls of their designs.

Implications for Lesson Design. In Chapter 2, I proposed four lesson criteria that, upon further investigation, afforded iteration to greater or lesser degrees. The lesson criteria that testing be encouraged in the classroom and that challenge specifications be testable and non-subjective has the strongest support from my data. In Chapter 3, students made frequent use of the formal testing station, and considered not only the specifications included in the challenge, but also emergent constraints derived from the context of the challenge (materials, narrative) when evaluating their solutions. Frequent testing and revision were the means by which students confirmed that they were meeting these specifications. In Chapter 5, I demonstrated that following a testing protocol with sufficient scaffolding from the teacher could shift student thinking from a less-subjective context through which students were framing a problem toward the context of the testing station, as envisioned in the planned curriculum, enabling their solutions to be critically assessed and revised. As was discussed in Chapter 5, evaluation of solutions is essential to instigating the revision of a design. Thus, the promotion of testing non-subjective specifications throughout the lesson afforded student iteration.

For the criteria that lessons not be "over-constrained," this research suggests that there is a fine line between optimizing students' critical evaluation of their design and railroading them toward one specific solution. In Chapter 3, the teacher was able to redirect students toward testable design solutions by clarifying one detail in the design challenge, that the solution had to be usable by the clients from the narrative context. Combined with Chapter 5, where the same class did not receive any clarification in their design challenge and their solutions were not compatible with the testing station, this indicates that young children benefit from "just in time" scaffolding and real-time guidance when negotiating a challenge statement in the classroom context. This also requires teachers to remain vigilant during lesson enactment to recognize when such scaffolding is necessary, and to predict its effect on student thinking and practice. Students likely would have entered into productive iterative cycles earlier in these lessons had they been instructed explicitly to build bridges or fences. In Chapter 4, however, the extremely ill-defined nature of the challenge afforded diversity in both design and approach, which did not provide limitations for iteration.

The last lesson criteria is to give students a role in defining the challenge. In Chapter 3, students exercised this freedom by defining emergent constraints on top of the explicit constraints established in the design challenge, even though this was not the intent of the planned curriculum. For students to meet these additional emergent constraints, more testing and revision was required, thus affording student iteration. In Chapter 4, students acted as the clients, motivated by the framing of the challenge as a competition to rapidly iterate upon their design and achieve the best results. In Chapter 5, the kindergarten students missed the connection of the Garden Pest lesson to the context of the classroom garden, right outside their door. They could have been re-directed by the teacher to recognize themselves as clients and build a solution more compatible with the testing protocol in the planned curriculum, thus affording iteration of their designs. The third-grade students did relate the Athletic Shoe challenge to their own experience with sports and footwear, but this did not provide affordances for meeting and testing relevant specifications as they constructed their solutions.

Implications for Teachers. Problems that professional engineers encounter in their workplace are classified as *ill-defined problems*; that is, problems where one or more aspects of the problem are not well defined, or the information needed to solve them is not in the problem; that possess multiple solutions, solution paths, or no solutions at all (i.e., the solutions are *divergent*); have vaguely defined goals and unstated constraints; and require people to make judgments about the problem or solution, and defend them, among other things (Chi & Glaser, 1985; Jonassen, 1997; Jonassen et al., 2006). This is in contrast to the most common problems students will learn to solve in traditional STEM classes, *well-defined problems,* where there is one right solution (i.e., the solutions are *convergent*); all of the information needed to solve the problem is given; and have a preferred, prescribed solution process (Jonassen, 1997; Jonassen et al., 2006). From my observations, elementary engineering design challenges can fall somewhere in between these two definitions. In order for elementary teachers to scaffold a more professional (i.e., open-ended and ill-structured) style of engineering design in their classrooms, they will require extensive content and pedagogical content knowledge (Kendall & Portsmore, 2013; Kendall & Wendell, 2012) so that they themselves are comfortable with understanding engineering design behaviors and the materials with which their students are building, and also are able to react productively to the uncertainties of an open-ended classroom, and the absence of "correct" answers. This includes accommodating emergent constraints, inventing new testing protocols on the fly, adding further definition to challenges when students have too many degrees of freedom, and allowing for experimental-based approaches to design.

Additionally, designers in the workplace most commonly encounter problem constraints that are related to the context of the problem/goal, such as time, budget, client wishes, materials and tools available (Jonassen et al., 2006), many of which are paralleled in classroom challenges. Studies have shown that experience solving well-structured problems does not always translate into skill solving ill-structured problems (Cho & Jonassen, 2002; Hong, Jonassen, & McGee, 2003). Given our desire for elementary engineering education to be *intellectually honest*, that is, what Bruner (1960) and Ball (1993) would describe as representing a domain in a way that is true to its professional form but accessible to young learners, posing ill-defined problems in the elementary classroom should best prepare students for real-life problem-solving situations. The context need not be identical to those professional engineers would face in order to encourage students to engage in engineering practices. Clients can be characters from literature (who happen to be billy goats) or the students themselves. The classroom chairs as the site of a bridge can provide challenges of geography, just as a sandy embankment of a river might. Improvements upon previous designs can produce optimal solutions for the specific challenge at hand. All of these contexts, achievable in the early-elementary classroom, will result in students utilizing engineering design practices in an *intellectually honest* way.

In elementary classrooms, the *Engineering Design Process* is often treated in a manner similar to the Scientific Method or the Writing Process (Cunningham

& Hester, 2007; Wendell et al., 2010) and is depicted as being a linear or circular series of steps, implying that even if the process repeats itself, each step should occur sequentially. This simplistic model of problem solving, which bears no resemblance to expert patterns of problem solving, has the potential to mislead students as to how design problems ought to be solved, and has caused problems in the classroom; teachers with a novice understanding of engineering design have been shown to render the process as a series of steps their students "had" to do, without imparting to the students the purpose and rationale for the steps (McCormick, 2004). This dissertation provides evidence that engineering design challenges in the classroom can be wildly successful without following the strict *engineering design process*. Plan-based approaches are effective, but so too are experimental-based ones, and other more bottom-up methodologies. Testing frequently and iterating rapidly belie the tendency to of classroom design challenges to allow for limited iterative cycles. Indeed, some degree of domain knowledge, which beginners may not possess, is necessary to engage in engineering practices such as planning. Allowing students to apply engineering practices toward their objective is of more importance than the overall structure those practices take within the activity.

Limitations

This study was limited by its context, situated within the classroom and subject to many competing variables and factors. As such, I can describe the lessons and student behaviors I observed in my research, but these findings will vary over other contexts. It is a tenet of situative perspectives that knowledge is embedded within the interactions between students, and between students and artifacts (Greeno, Collins, & Resnick, 1996). Thus, the extent to which any research is generalizable is open to debate. Methodologically, I chose a qualitative case-study approach precisely because it was highly situative in nature, and a narrative approach in order to focus on story and context. However, my methodology would not be readily scalable for studying an entire classroom, let alone hundreds of students.

Some might take exception to the heavy reliance of narrative reporting of data, rather than use of coding analysis or transcript excerpts. However, narrative analysis is becoming an increasingly accepted paradigm within the engineering education research community (Case & Light, 2011). I also believe the adoption of activity theory assisted by grounding my analysis in well-established theoretical framework. My research is by necessity descriptive and observational in nature because there were few existing studies of early-elementary students design to build upon. Future studies may be able to propose causal hypotheses based on this work, and the related work of my colleagues.

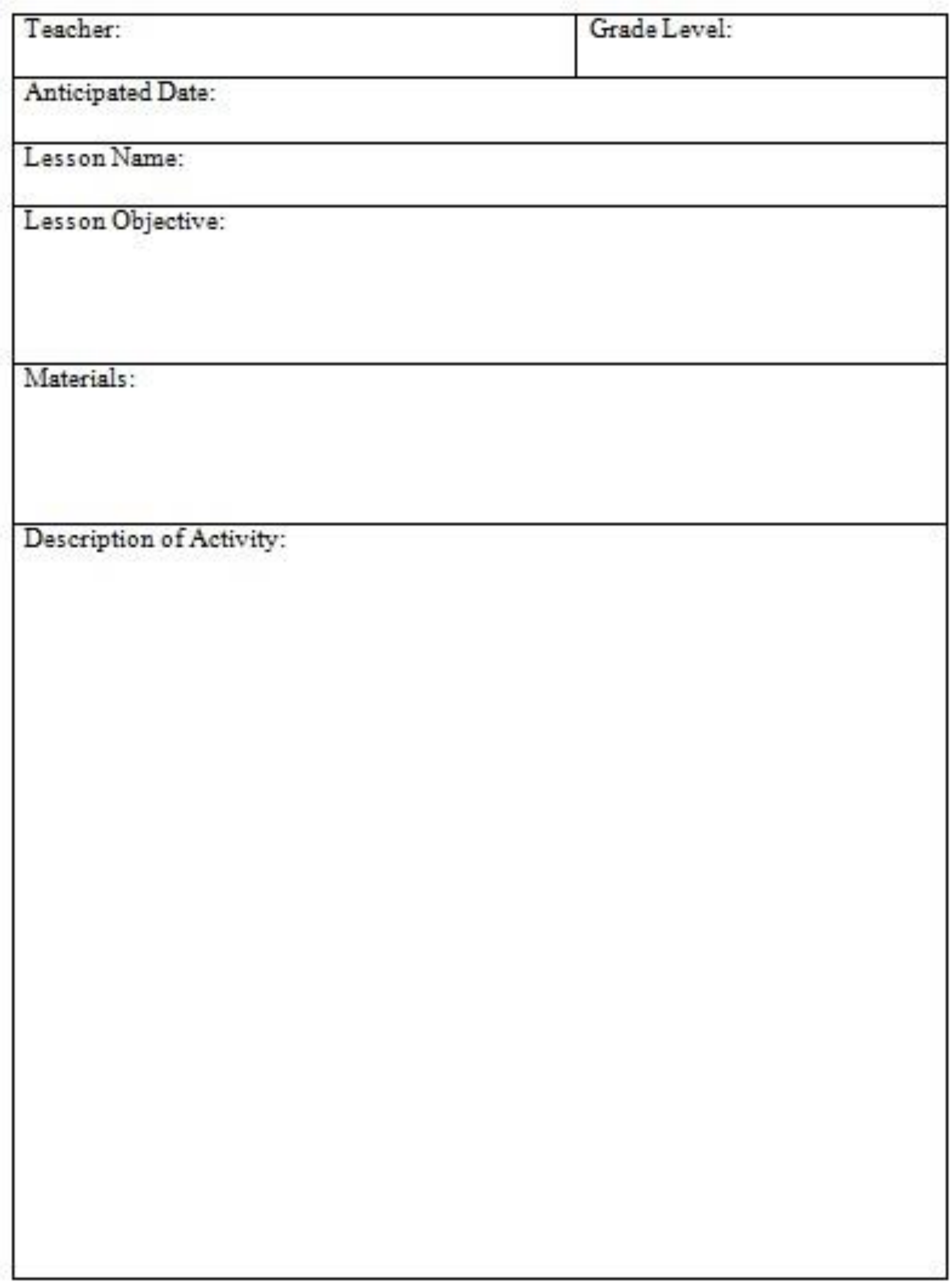
Recommendations for Future Work

My work, and that of my colleagues, has made great strides in the last few years toward describing the engineering design behaviors of elementary students (Hynes & McCormick, 2012; McCormick & Watkins, 2015; Portsmore, 2010; Wendell et al., 2014; Wendell & Lee, 2010; Yang et al., 2015). There are several avenues for following up on my research in order to further explore questions regarding the social interactions between students, and the interactions between students and materials. For instance, the two lessons enacted in the kindergarten classroom (building a long and strong bridge, and building a garden to keep pests out and let sunlight and water in) could be accomplished with either LEGO® or common craft materials. Given two classrooms, all four permutations of challenge and material could be examined to explore the relationship between materials and student engineering behavior. Potential research questions include: Does working in LEGO® materials influence the frequency of "pretend," or untestable solutions, or the frequency of testing itself? Does the easy-to-disassemble-and-reassemble nature of LEGO® materials increase the frequency of iterative design cycles? Additionally, one group in the third-grade classroom had difficulty settling into either a plan-driven or experimentation-driven process for designing. It would be helpful to find more productive examples of students engaged experimentation-driven problem solving, and to examine what happens if group consists of students who prefer different styles. This could lead to assisting teachers in forming harmonious student groups for design challenges.

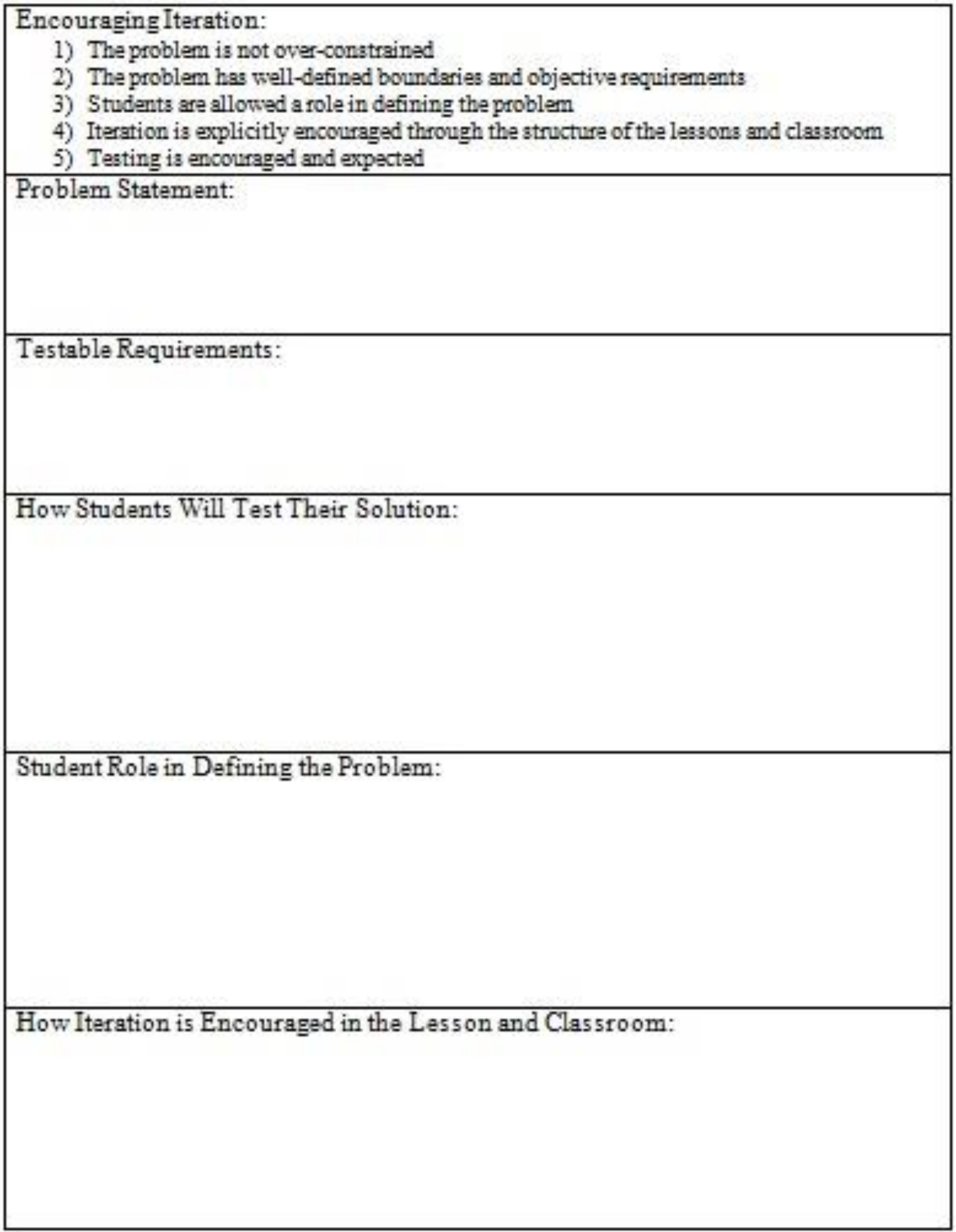
The biggest question derives from the implications of the research project of which this dissertation is a part. Very few people have examined engineering design behavior at the early-elementary level because very few early-elementary classrooms incorporate engineering into their curricula. But examining kindergartners engaged in engineering design introduces the question, what do college-freshman engineering practices look like if those freshmen have had thirteen prior years of engineering experience? Obviously, the widespread exposure of engineering at the K-12 level is too new, and the scope of this study is not broad enough, to answer that question. Given the potential we see in the youngest students, what effects of integrating engineering into the pre-college curriculum will manifest in the preparedness or diversity of future engineers?

Appendix A: Planning Worksheets for Students and Teachers

Lesson Planning Worksheet

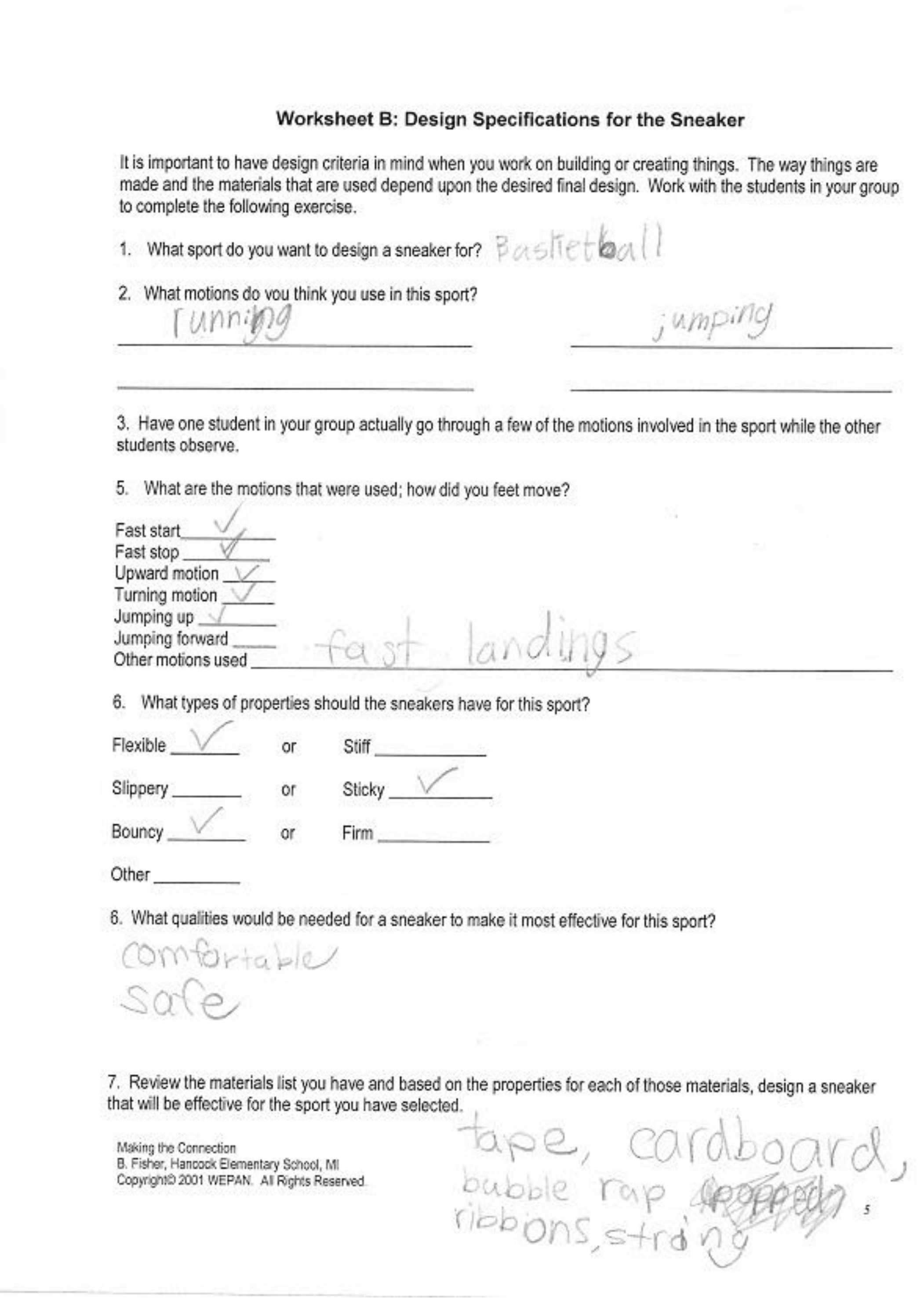


Teacher:	Grade Level:
Anticipated Date:	
Lesson Name:	
Lesson Objective:	
Materials:	
Description of Activity:	



Encouraging Iteration: 1) The problem is not over-constrained 2) The problem has well-defined boundaries and objective requirements 3) Students are allowed a role in defining the problem 4) Iteration is explicitly encouraged through the structure of the lessons and classroom 5) Testing is encouraged and expected
Problem Statement:
Testable Requirements:
How Students Will Test Their Solution:
Student Role in Defining the Problem:
How Iteration is Encouraged in the Lesson and Classroom:

Planning Worksheet for the Athletic Shoe Challenge



Worksheet B: Design Specifications for the Sneaker

It is important to have design criteria in mind when you work on building or creating things. The way things are made and the materials that are used depend upon the desired final design. Work with the students in your group to complete the following exercise.

1. What sport do you want to design a sneaker for? Basktetball

2. What motions do you think you use in this sport?

running

jumping

3. Have one student in your group actually go through a few of the motions involved in the sport while the other students observe.

5. What are the motions that were used; how did you feet move?

Fast start ✓
Fast stop ✓
Upward motion ✓
Turning motion ✓
Jumping up ✓
Jumping forward ____
Other motions used fast landings

6. What types of properties should the sneakers have for this sport?

Flexible ✓	or	Stiff ____
Slippery ____	or	Sticky ✓
Bouncy ✓	or	Firm ____
Other ____		

6. What qualities would be needed for a sneaker to make it most effective for this sport?

comfortable
safe

7. Review the materials list you have and based on the properties for each of those materials, design a sneaker that will be effective for the sport you have selected.

tape, cardboard, bubble rap ~~[illegible]~~ ribbons, string

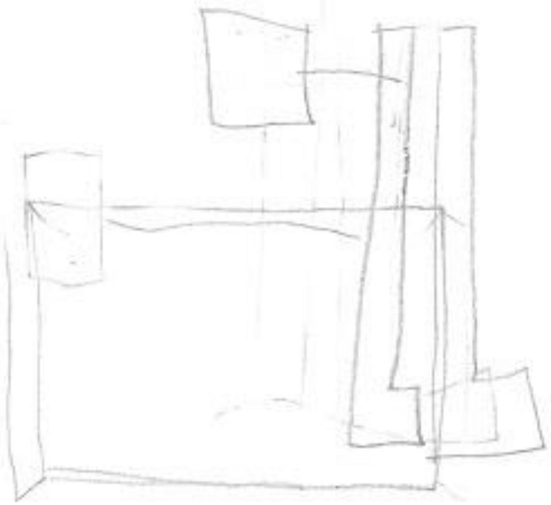
Making the Connection
B. Fisher, Hancock Elementary School, MI

Planning Worksheet for the Marshmallow Thrower Challenge

The Great Marshmallow Challenge!

Group Name: Bady Ruth	
Project Manager:	Materials Manager:
Recorder:	Reporter

Sketch an idea for your marshmallow thrower here. You can use the back of this page if you run out of room.



How will you use the motor? To make the foot Move
What other pieces will you need? Moter battery pack

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