

MIDDLE-SCHOOL TEACHERS' USE AND DEVELOPMENT OF ENGINEERING

SUBJECT MATTER AND PEDAGOGICAL CONTENT KNOWLEDGE:

A PILOT STUDY

A qualifying paper

submitted by

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Abstract

This paper reports on a study of two middle-school math and one middle-school science teacher as they taught an engineering unit. The study investigated the subject matter knowledge and pedagogical content knowledge these teachers used and developed as they taught an engineering unit that used LEGO to teach students the engineering design process through designing and building an assistive device that uses motors, sensors, and is computer controlled. Data collected from teacher interviews and classroom observations revealed the different subject matter and pedagogical content knowledge the teachers used to teach engineering that was new for them. The data revealed how a teacher's knowledge of physics or engineering can impact their teaching. The data also highlighted that the teachers rarely explicitly used their math or science knowledge to make connections to engineering. The study also illustrated examples of engineering pedagogical content knowledge the teachers developed while teaching the engineering unit. One central conclusion drawn from the study is that teachers would benefit from focused opportunities to develop the different specific types of engineering knowledge that they struggle with the most (i.e., physics concepts, mathematics principles, engineering design). The paper includes a literature review that provides a rationale and framework for studying the teaching of middle-school engineering, a description of the methods used, and results and implications of this study.

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Introduction

The purpose of this study is to explore the knowledge middle-school math and science teachers use and develop as they teach engineering in an afterschool program. The study, specifically, investigates what math, science, and engineering subject matter knowledge and engineering pedagogical content knowledge they use and develop. Similar research has been conducted looking at math and science teaching; however, little research has been done regarding teaching middle-school engineering. Engineering is a unique subject area, which adds to the complexity of understanding what knowledge teachers need and use in teaching the subject. Engineering is the process of applying different domains of knowledge (i.e., science, mathematics, economics, human psychology, etc.) to the design, evaluation, and redesign of technological ends. The study reported in this paper investigates three middle-school teachers and the knowledge they use and develop as they take on the challenge of teaching an engineering curriculum. The teachers are all in-service teachers who do not teach engineering as their primary subject. The two research questions the study seeks to answer are:

1. *What math, science, and engineering subject matter knowledge do middle-school math and science teachers draw upon and incorporate as they teach an engineering unit?*
2. *What engineering pedagogical content knowledge do middle-school math and science teachers know, use, and develop as they teach an engineering unit?*

Prior to describing the study and the results, I will define what engineering may look like in the middle-school classroom, and review literature on subject matter and pedagogical content

knowledge the two bases of teacher knowledge about which the study is framed. Then, I will describe the curriculum and methodology for the study. Finally, I will present the results, discuss the results, and describe possible implications of the results.

Engineering in the Middle School Classroom

Engineering education in the United States K-12 setting is a new idea that has been gaining attention as professional and educational groups continue to push for its inclusion into the pre-college classroom (International Technology Education Association, 2002; McAdoo, 1998; National Research Council, 2005). Currently, Massachusetts is the only state that includes engineering in its state curriculum standards (Massachusetts Department of Education [DOE], 2006). However, national science and technology associations have started to include some engineering concepts in their science and technology standards (International Technology Education Association, 2002; National Research Council, 2005). Other countries such as the United Kingdom, Australia, New Zealand, and Canada have already included design and technology in their pre-college curriculum (Curriculum Council, 1998; Ministry of Education, 2007; Newfoundland and Labrador Department of Education, 2007; United Kingdom Qualifications and Curriculum Authority, 2007)

The International Technology Education Association (ITEA) places engineering design within the context of technology education and describe engineering design as demanding “critical thinking, the application of technical knowledge, creativity, and an appreciation of the effects of a design on society and the environment” (2002, p. 99). The National Research Council (NRC) (2005) recognizes the importance of the relationship between the fundamentals of science and the process of technological design as they include science and technology standards within their national science education standards document. The NRC describes

fundamental abilities and concepts in technological design as identifying problems, designing solutions or products, implementing designs, evaluating designs, and communicating the process of technological design. There are certainly parallels between how the NRC describes technological design and the ITEA describes engineering design. Both include a design process and the use of knowledge and skills from various domains (i.e., math and science) to design and create solutions to problems.

Other countries have been including some form of technology or engineering in their national curriculums. The United Kingdom includes a “Design and Technology” strand for their primary and secondary education frameworks (United Kingdom Qualifications and Curriculum Authority, 2007), Australia includes what they call “Technology and Enterprise” (Curriculum Council, 1998), New Zealand and Canada also include similar design curriculums (Ministry of Education, 2007; Newfoundland and Labrador Department of Education, 2007). These are just a few of the countries including technology or engineering subject matter in their pre-college curriculums. Each of these countries’ design, technology, or engineering strands includes some version of a design process as well as the knowledge and skills used in designing or engineering.

Engineering, technology, and design are interspersed throughout the various curricular standards and guidelines highlighted above. Each term could be defined within the context of middle-school education and then used to describe the central subject matter discussed in this study. For this study, engineering will be used to describe the subject matter in this study. The rationale for using the term engineering is that it can be used as a verb describing an active process, includes the concept of engineering design (more precise for this study than the more general term design), and refers to the domain of a profession the subject matter is trying to emulate.

If engineering is the subject matter, what exactly does that mean? The aforementioned curricular standards each define and highlight different parts of engineering, technology, and design slightly differently. However, they all follow a similar model where some knowledge (e.g., math, science, engineering, and technology) is applied through some process (e.g., the engineering design process) to create some technological product or end. Engineering is not limited to engineering, scientific, and mathematical principles and can include principles of history, social science, and economics as highlighted by educational standards (International Technology Education Association, 2002). The design process—application portion of the definition—involves weighing the benefits, costs, and constraints of design options that arise from these domains of knowledge. The technological products or ends are not always physical products, they can be systems or processes, algorithms, or procedures. The specific technological end (i.e., bridge design or robotics) within the field of engineering will serve as the context for the engineering design process. For the school setting, this specific topic should be engage students and be something they can relate to. These content areas draw upon math and science concepts that students are learning and have learned. Engineering is then the process of systematically applying knowledge to the design, evaluation, and redesign of technology. In education, engineering can be seen as a process through which we teach science, technology, engineering, and math. Through this process, students construct and connect knowledge through their real-world artifacts akin to Papert’s (1980) constructionism.

Accredited college engineering programs are required to include math and science courses, engineering design courses, and engineering science courses in their standard curriculum (Accreditation Board for Engineering and Technology, 2006). For the purpose of this study, middle-school engineering will have the engineering design process as a central concept

the students will use and understand. The engineering design process was chosen because it is not realistic to expect middle-school students to engage in advanced math and science classes similar to that of college engineers or in engineering science classes that include specialized content (e.g., thermodynamics, fluid dynamics, circuitry, etc.). The engineering design process, on the other hand, can be simplified for use at this grade level, is central to many fields of engineering, and does not require teachers to have specialized knowledge in myriad fields. With the engineering design process as a central theme, grade-level appropriate math, science, and selected engineering science concepts can be introduced to middle-school students to be applied in their designs, but won't necessarily be the crux of the curricula.

The statement that a generic engineering design process is central to most of engineering is debatable (Lawson, 1997). Each field of engineering has distinct engineering design processes that differ based on the resulting product, system, or process. Many models of the engineering design process exist, and there is no one correct or universal model. However, there is some agreement as to what they have in common, which Cross and Roozenburg (1993) refer to as the consensus model. The idea behind this model is that it “does not restrict designers to just one way of working. Instead, it tries to organize the problem-solving behaviour of designers so that this behaviour will be more effective and efficient than intuitive, unaided, unsystematic ways of working” (Cross & Roozenburg, 1993, p. 328). The Massachusetts DoE (2006) has included a model of the engineering design process (see Figure 1) in their curriculum frameworks document that includes key features as described in the consensus model written in language more appropriate for a middle-school student. In this model, students: identify the need or problem to address; research the need or problem; brainstorm possible ways to solve the problem; select the best way to solve the problem; construct a prototype or model of their solution; test and evaluate

their solution; communicate their solution; and redesign their solution or prototype. One drawback of this representation of the engineering design process is that it does not illustrate the web-like nature of the engineering design process where you might jump back from one step to another as is shown in the model of the design process the Labrador and Newfoundland school authority uses shown in Figure 1. Given that the study presented in this paper is conducted in Massachusetts, the engineering design process in Figure 1 (right) is what the teachers and students will be using as a model throughout the curriculum. However, during the teacher professional development workshop the web-like nature of the engineering design process is stressed to the teachers.

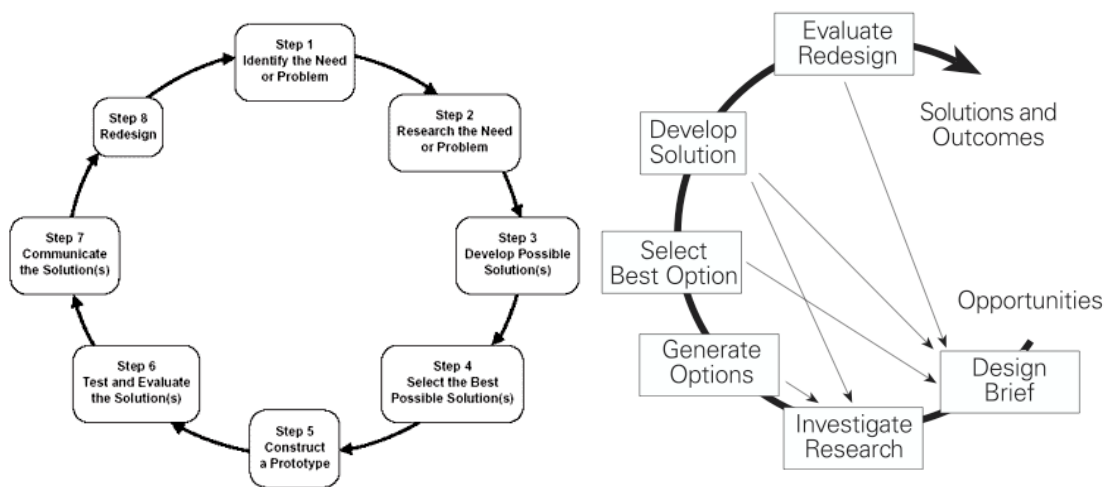


Figure 1: (Left) Massachusetts DoE Design Process (Massachusetts DOE, 2006). (Right) Canadian Design Process (Newfoundland and Labrador Department of Education, 2007).

To have the engineering design process be a central concept for the middle-school classroom, there must also be a context for it to be taught within. Or in other words, what will students apply this process to? Again, there are many fields within engineering that could be chosen for this. The Massachusetts DoE, for example, named several content areas within these

various fields as appropriate for middle-school engineering: materials, tools, and machines; engineering design; communication technologies; manufacturing technologies; construction technologies; transportation technologies; and bioengineering technologies. The diversity in engineering fields and content areas allows teachers to select content they have more experience with where they can then make connections to math and science concepts they know.

For the study presented here, teachers used robotics as the context for engineering to teach the engineering design process and basic engineering principles (e.g., gears, computer programming, construction, and electronics). Robotics is an interdisciplinary field within engineering that benefits from mechanical engineering, electrical and electronic engineering, computer science, biology, human factors, and many other disciplines (Niku, 2001). Robotics is the application, study, and design of using computer-controlled devices (robots) to perform tasks for human endeavors. The interdisciplinary and open-ended nature of robotics enables teachers and students to explore and apply hosts of math, science, and engineering concepts to real-world problems. The specific curriculum, which takes advantage of the LEGO robotics toolset, will be detailed later in the *Methodology* section of this paper.

Teacher Knowledge

For students to be taught engineering and the engineering design process, teachers will need to be prepared to teach them. Teaching requires much more than just knowledge of the subject matter being taught (Ball, 1990, 2000; Ball & Bass, 2003; Borko & Livingston, 1989; Borko et al., 2000; Darling-Hammond, Berry, & Thoreson, 2001; Lampert, 1986, 1990; Ma, 1999; Rowan, Correnti, & Miller, 2002). Shulman (1987) recognized a large base of knowledge for teaching that includes: content knowledge; general pedagogical knowledge; curriculum

knowledge; pedagogical content knowledge; knowledge of learners; knowledge of educational contexts; and knowledge of educational ends, purposes and values. Grossman (1990), working from Shulman’s categories of knowledge, simplified a teacher’s knowledge base (see Table 2) so that pedagogical content knowledge subsumes a number of Shulman’s categories of knowledge. These categories of knowledge illustrate that a teachers need to know more than the subject matter. Teachers need to know how to ask questions, what their students’ abilities are, and how to design curriculum. These issues are not simply addressed by taking advanced college courses in the content area. Moreland and Jones (2000) findings support the categories of knowledge as simplified by Grossman. They found technology teachers needed to develop three interdependent domains of knowledge—“knowledge of technology, concepts in technology education, and primary school pedagogical knowledge of technology” (Moreland & Jones, 2000, p. 284).

Table 1: Teacher knowledge base categories of Shulman (1987) and Grossman (1990)

Condensing the teacher knowledge base	
Shulman	Grossman
Content knowledge	Subject matter knowledge
General pedagogical knowledge	General pedagogical knowledge
Knowledge of educational contexts	Knowledge of context
Pedagogical content knowledge	Pedagogical content knowledge
Knowledge of learners and their characteristics	
Curriculum knowledge	
Knowledge of educational ends, purposes, and values	

Teacher Knowledge in Engineering

The study presented in this paper investigates in-service middle-school math, science, and technology teachers as they implement a new engineering unit focusing on the engineering design process and robotics in in-class or after-school classrooms. The goal of the study is to see what knowledge the teachers draw upon and develop as they teach this engineering unit. For this study, the focus will be on the teachers' use and development of math, science, and engineering subject matter and pedagogical content knowledge. This focus complements the work of Moreland and Jones (Jones & Compton, 1998; Jones & Moreland, 2004; Moreland & Jones, 2000) who have conducted a number of studies on technology teacher education and development. Their findings reveal that a teacher's concept of technology, knowledge of technology, and knowledge of teaching within technology impact their teaching and their students' outcomes. This study aims to reveal similar findings for teaching engineering. The following two sections expand on the impact of a teacher's subject matter and pedagogical content knowledge on their teaching and their students' learning.

Teaching engineering requires math and science subject matter knowledge as well as engineering specific knowledge. Middle-school engineering teachers will apply math, science, and engineering knowledge to help students address the engineering problems contained in the engineering unit. They will also apply and develop new pedagogical content knowledge, which is the knowledge of how to teach a specific topic or subject. Their pedagogical content knowledge will include: knowledge of what their students know about engineering concepts; real-world examples that help students connect their knowledge to engineering concepts; and strategies to guide students through engineering challenges. What follows is a review of literature on both subject matter and pedagogical content knowledge to establish the context for

this study. The literature primarily explores teaching and learning math and science. Research in math and science education has had significantly more time to mature than that in engineering education. Since engineering employs math and science knowledge, these two fields of research elicit some of the most relevant connections to engineering education.

Subject Matter Knowledge for Teaching

Ball and McDiarmid (1990) argue that a pupil will only be able to gain as deep an understanding of the subject matter as their teacher has. Clearly it is important to understand a teacher's knowledge of the subject they are teaching. However, to this point teachers have not been receiving certification to teach engineering or engineering content courses as part of their preparation. Ill-defined engineering design tasks make it difficult to predict what specific subject matter knowledge is required. It will be important for this study to capture and recognize the use and development of teachers' engineering knowledge as they guide their students through the engineering design process, as well as the teacher's application of relevant math and science knowledge to the engineering design tasks.

How much a teacher knows about a subject certainly impacts their ability to teach that subject. But just how much does a teacher need to know to support solving engineering design problems? What are the implications if they do not know *enough*? What does it mean to *know* a subject? And how much is *enough*? These questions may never be answered in absolute terms, but research can guide teachers and educators to make decisions regarding teacher preparation and development. Studies have investigated questions like these in the content areas of mathematics and technology (Apple, 1992; Ball & Bass, 2003; Cohen & Ball, 1990; Jones & Compton, 1998; Jones & Moreland, 2004; Lampert, 1986; Ma, 1999; Moreland & Jones, 2000).

This section will focus on findings from studies investigating teachers' subject matter knowledge and how it can impact his or her teaching.

The content area of mathematics has traditionally been a focal point in national educational policy, and, has an extensive body of research investigating teachers' math subject matter knowledge and its impact on teaching. Ma (1999) developed and carried out a study looking at the depth of teachers' subject matter knowledge in elementary mathematics. The study focused on Chinese and United States (U.S.) teachers' understanding of arithmetical operations such as multi-digit multiplication and dividing using fractions. Ma found that the Chinese teachers had a much deeper knowledge of these operations than the U.S. teachers who had taken more advanced mathematics courses in college (e.g., calculus). When asked to provide explanations for different facets of these operations, the Chinese teachers greatly outperformed the U.S. teachers. For example, Ma reported, "61% of the U.S. teachers and only 8% of the Chinese teachers were not able to provide authentic conceptual explanations for the procedure [of multi-digit multiplication]" (Ma, 1999, p. 52). Ball (1990) revealed a similar lack of depth in understanding among prospective U.S. teachers. All teachers in her study were able to perform tasks such as dividing $1\frac{3}{4}$ by $\frac{1}{2}$, but less than half of both prospective elementary and secondary teachers were able to generate appropriate representations to explain the underlying principles in the problem. Relying primarily on a teacher's prior coursework does not always predict how well a teacher understands the basics or how well they will be able to teach the subject.

More recently, Hill, Rowan, and Ball (2005) found that a teachers' mathematical knowledge was significantly related to students' achievement. Their assessment of teachers' mathematical knowledge went beyond the traditional metrics of number of courses or degrees attained to include a measure to elicit the mathematical knowledge a teacher uses in the

classroom. The assessment presented teachers with examples of students' math work (e.g., multi-digit multiplication calculations), and asked the teachers to analyze and assess the students' thought processes and understandings. Hill, Rowan, and Ball (2005) were assessing mathematical knowledge a teacher would actually use in the classroom rather than simply what the teacher knew about math. This measure proved to be a significant predictor of students' test scores, while the teachers' college coursework, certification, and years of experience were not. Other studies have shown that teachers with greater subject matter knowledge are better able to lead their classrooms in inquiry exercises focusing on conceptual and problem solving topics (Borko et al., 2000; Borko & Putnam, 1996; Davis, 2003). These teachers have a better understanding of the underlying mathematical or scientific principles and are able to address the multitude of student viewpoints by identifying the underlying principles that are behind the students' ideas and questions.

This leads to the question, what does a teacher need to know about a subject to teach that subject? Lampert (1986) broke down the subject matter of math into intuitive knowledge, computational knowledge, concrete knowledge, and principled knowledge. These types of knowledge can be defined as follows:

- Intuitive knowledge – knowledge not formally taught in school but developed through one's intuition or in the field of practice.
- Computational knowledge – the formal knowledge learned in school for calculations (e.g., multiplication).
- Concrete knowledge – the mathematical knowledge that can be used to manipulate objects to come to an answer (e.g., using chips to form five groups of four to represent multiplication).

- Principled knowledge – conceptual knowledge of mathematics or the distinction between knowing how to perform a calculation to get the answer and understanding how the calculation works to get the answer.

Lampert noted that the ability to connect all these types of knowledge is what constitutes teaching mathematics. Ball and Bass (2003) highlighted that knowledge for teaching includes a much deeper understanding of the subject matter so teachers “use appropriate definitions... use mathematically appropriate and comprehensible explanations... represent ideas carefully... respond appropriately to students’ questions and curiosities” (p. 11). Similarly, in technology, Jones and Moreland found that the teacher’s knowledge of technology directly impacted their students’ learning (Jones & Moreland, 2004). Teachers with a poor concept of technology and unable to relate the nature of technology (viz., the how and why of technology) to the subject matter of technology left their student’s with poor understandings of this connection. Instead, students were left with a simplistic concept that technology is merely making things. Then after teacher professional development these same teachers were able to impact their students understanding to include a broader more accurate representation of the nature of technology. The corollary in an engineering design project may be teachers “making” students complete each step of the engineering design process before moving on to the next without any explanation beyond, “because that is the way it is done.” It is apparent that subject matter knowledge is critical in a teacher’s ability to teach, and supports the notion of the interdependence it shares with pedagogical content knowledge.

Pedagogical Content Knowledge for Teaching

The previous section highlighted the importance of a teacher's subject matter knowledge. The latter part of the discussion highlighted that knowing the subject matter for teaching includes a deep understanding of the subjects' underlying principles, how they connect, and the how the subject matter is situated in the world. For example, in mathematics a person with strong computational knowledge does not necessarily understand the mathematical concepts behind the computations. In engineering, a teacher will need to know more than what the engineering design process is, they will have to know how to engage students in ways that the students are applying their knowledge to designing solutions. This leads to what some refer to as pedagogical content knowledge (Gess-Newsome, 1999; Shulman, 1987). Pedagogical content knowledge is knowledge specific to a subject or content area regarding *how* to teach and includes:

- Knowledge of students – understanding their misconceptions (content specific), what they struggle with, how they are unique, etc. (Driel, Verloop, & Vos, 1998; Gess-Newsome, 1999; Magnusson, Krajcik, & Borko, 1999; Peterson, 1988; Shulman, 1986, 1987; Veal, Tippins, & Bell, 1998).
- Real-world and appropriate examples – examples the teacher uses to link what is being taught in the lesson to examples the students can relate to (Davis, 2003; Gess-Newsome, 1999; Magnusson, Krajcik, & Borko, 1999; Shulman, 1986, 1987).
- Strategies for student understanding - strategies a teacher uses to help foster and deepen the students understanding of the specific content or material (Driel, Verloop, & Vos, 1998; Veal, Tippins, & Bell, 1998).
- Classroom management - methods of managing the lesson that are specific to the content (i.e., engineering) being taught (Shulman, 1986).

Traditionally, this kind of knowledge is not easily assessed or systematically developed in the way subject matter knowledge is (Baxter & Lederman, 1999; Rowan et al., 2001). It is knowledge that, for the most part, is slowly developed while teaching students in the classroom (Veal, Tippins, & Bell, 1998). Many in the field refer to this as the knowledge necessary to teach a subject (Gess-Newsome, 1999; Shulman, 1987; Veal, Tippins, & Bell, 1998). For teaching engineering, this knowledge could include a teacher knowing how to guide students' through the engineering design process while they work through a challenge, what issues students might have as they learn to implement gears, or powerful real-world examples of the concept of torque.

The first category of knowledge listed—*knowledge of students*—may be the most critical in teaching. According to Shulman, knowledge of students is something that, “should be included at the heart of our definition of needed pedagogical knowledge” (1986, p. 10). More explicitly, this knowledge of students is understanding students' current knowledge and cognitive abilities, their common misconceptions or difficulties with certain topics and ideas, and contexts and examples that appeal to them (Berliner, 1986, 1994; Gess-Newsome, 1999; Shulman, 1986). Understanding a child's cognitive ability can be complicated as is exemplified by the many theories and models that exist for children's cognition. The theories and models the different abilities, processes, and intelligences children and adults employ (Ackerman & Lohman, 2006; Gardner, Kornhaber, & Wake, 1995; Sternberg, 1999). (Ackerman & Lohman, 2006; Sternberg, 1999) No matter which theory or model one prefers, it is clear that each student has different abilities and may learn differently than his or her classmates. Furthermore, Strauss (1993) found that teachers have their own mental model of how children learn or how their minds work, and that this often dictates how they approach teaching their students. If a teacher's mental model of how children learn is limited, it can constrain educational goals they set for their

students. Children's minds and how they learn are different for students of different ages and different for each student across different subjects (Strauss, 1993; Strauss, Ziv, & Stein, 2002). Further evidence for this need is provided by Confrey (1991), who posits that the nature of constructivist methods of teaching calls for listening to students and devoting considerable time to understanding students' views of problems. In each subject and each topic there are myriad ways to approach and solve problems. This is especially true in engineering where each student could have a unique solution to the same problem.

Furthermore, studies have shown a positive correlation between how much a teacher knows about their students and the students' achievement. Carpenter *et al.* (Carpenter, Fennema, Peterson, Chiang, & Loef, 1989) found that teachers who engaged in rigorous study of research-based analysis of children's development of problem-solving skills in addition and subtraction had a significant positive impact on their students' achievement. These teachers spent more of their time engaging their students in problem-solving activities than did the control group teachers, and less time on number fact activities. Carpenter *et al.* noted that these results were not easy to achieve and were the product of four weeks of focused workshops considering only the concepts of addition and subtraction. With more time teachers could develop these understandings for more and more topics. Berliner (1994) recognized that expert teachers had excellent pattern recognition capabilities in their classroom. He noted that expert teachers, just from observation, were able recognize what students were doing, whether or not they were motivated, or deep in thought just from observations. The novice teachers identified only the obvious surface features (e.g., the students are reading or they are working in groups) in their observations. Again, understanding multiple viewpoints and student understanding will play a role in teaching engineering, which result in students' generating more varied ideas and

solutions. There is plenty of room for new research in this area, and this study looks to frame and guide future research.

The other four categories of pedagogical content knowledge—real-world examples, appropriate examples, strategies for student understanding, and lesson management—are possible to observe a teacher actually *doing* in the classroom. They could be considered what makes up the practice of teaching a specific subject. Using *real-world examples* that relate the concept at hand to the students' lives has proven to reinforce students' understanding and promote retention (Korwin & Jones, 1990). Shulman (1986, 1987) recognizes that teachers need to be able to represent material in many different ways for their many different students. Real-world examples are one such representation. In engineering design projects these real-world examples often take a hands-on, physical approach. Bamberger (1991) highlighted that not only is it important for the teacher to understand how to help students move from real-world representations to knowledge, but to also understand how they (the teachers) move from real-world representations to constructing knowledge. Engineering is filled with these types of real-world examples and representations. For example, a lesson on gears could be illustrated with examples involving bicycles, cars, eggbeaters, and computer CD trays. Likewise, the many different cell phones and music players companies have developed could highlight the generating solutions step in the engineering design process. Effective engineering teachers will likely be able to generate real-world examples that meaningfully connect engineering concepts to students' lives.

Being able to *identify and choose appropriate examples* is another critical ability in teaching (Magnusson, Krajcik, & Borko, 1999). For a teacher to differentiate between examples and determine what each example highlights for a topic requires both understanding of the

subject matter as well as knowledge of his or her students. This could be measured by giving teachers teaching scenarios and project artifacts and asking which is most appropriate for a teaching challenge and why. Choosing such examples may be included in the category of *strategies for student understanding*. Strategies for student understanding includes the examples, representations, activities, and other practices a teacher uses with the aim of deepening the students understanding of the subject or topic at hand.

Classroom discussion is a strategy teachers employ to encourage students to “discover” and “invent” mathematical and scientific concepts. Lampert (1990) writes that learning mathematics has, traditionally, been:

Shaped by school experience, in which *doing* mathematics means following the rules laid down by the teacher; *knowing* mathematics means remembering and applying the correct rule when the teacher asks a question; and mathematical *truth is determined* when the answer is ratified by the teacher. (Lampert, 1990, p. 32)

Lampert argues that within this traditional view, there is no “process of coming to know” (1990, p. 30) mathematics for the students. Students may come out knowing what to do in certain situations, but may lack depth of mathematical knowledge. Classroom argumentation gives students the opportunity to make and discuss their conjectures, grapple with misunderstandings, and *come to know*. This strategy is similar to inquiry-based teaching methods, which are a central component of science learning and require teachers to guide their students in an inquiry, as *come to know* (Krajcik et al., 1998; Roth, 1995). These strategies do not reduce the role of the teacher, instead they call on the teacher to be even more masterful, like a conductor, guiding the students through the process of learning new concepts (Darling-Hammond, 2006; Driel, Verloop, & Vos, 1998; Lampert, 1990).

For each subject area there is an abundance of strategies to help develop student understanding. The study reported in this paper attempts to shed some light on a few strategies the teachers employ and develop as they teach engineering. The study will also highlight the *lesson management practices* the teachers use in their engineering unit. For example, are they adding or subtracting lessons from the curriculum, or how are they organizing the groups of students?

The Interaction Between Subject Matter and Pedagogical Content Knowledge

While subject matter and pedagogical content knowledge are considered two separate bases of knowledge for teaching, they are intimately related. Pedagogical content knowledge is highly dependent on knowledge of the content—or subject matter—as the name implies. A teacher with limited subject matter knowledge will likely not be able to develop strong pedagogical content knowledge. A teacher without adequate subject matter knowledge will not see potential misconceptions or struggles the students may be about to encounter and guide them into a trajectory of high learning potential. In a research setting where a teacher is being observed, subject matter knowledge is difficult to assess. While observing a teacher in the classroom you hear what they say and see what they do. Frequently, what you see and hear is more closely related to pedagogical content knowledge because this is the knowledge used to teach. Subject matter knowledge can sometimes be observed in what they say to a student, but most of that knowledge remains implicit as they ask students questions or guide them to try something new. This type of knowledge will best be revealed through teacher interviews. The study reported in this paper focuses on both bases of knowledge because it is not entirely clear the depth of subject matter knowledge that is needed for engineering design tasks, and observing

teachers in action is likely to reveal more of their pedagogical content knowledge, which, in turn, may reveal the important subject matter knowledge intertwined within it.

Subject Matter and Pedagogical Content Knowledge Framework

In this study, teachers will be using and developing both knowledge of engineering and knowledge of how to teach engineering. The *Subject Matter Knowledge* section of this paper outlined the impact and importance of teachers having well-developed subject matter knowledge in the subject they are teaching. In assessing students' work or monitoring classroom discussions, teachers need knowledge beyond what is in the textbook or the curriculum. The notion of subject matter knowledge is further complicated in engineering. The *Engineering in the K-12 Classroom* section illustrated that engineering is made up of multiple subject areas, most notably, math and science. Knowledge of engineering is also made up of technical know-how, knowledge of functional rules, and other knowledge that is commonly acquired in experiential activities. While a teacher with an engineering degree would likely have well-developed knowledge in each of these domains, it is unclear whether someone with a math or science degree along with some engineering experience (e.g., built a house) has sufficient engineering knowledge for the middle-school classroom.

As the *Pedagogical Content Knowledge* section of this paper highlights, knowing how to teach using a robotics design task is much more involved than just doing it by oneself. What teaching methods work well to have students apply mathematical and scientific knowledge as they work through design projects and actually create engineering artifacts? Most of engineering is devoid of right answers; instead, there are multiple solutions that address the needs and constraints of a problem in diverse ways. Teachers will not be able to solely rely on what they

know and will have to become designers alongside their students. The teachers will work with the students as they progress through the engineering design process and need to be able to troubleshoot on the spot. Even someone with an engineering degree will need to develop pedagogical content knowledge so as to be able to teach engineering to a select group of students. The framework this study starts from is how teachers' math, science, engineering, and engineering design support their development of pedagogical content knowledge. This study will likely create more questions than it does answers. Each new question may allow for myriad new solutions that can be applied to teaching engineering.

Methods

Study Design

The study was designed to answer the following questions:

- 1. What subject matter knowledge do middle-school math and science teachers draw upon as they teach an engineering unit?*
- 2. What engineering pedagogical content knowledge are middle-school math and science teachers using and developing as they teach an engineering unit?*

The first question considers the subject matter knowledge teachers will draw upon and use as they teach the engineering unit. It does not include subject matter knowledge they may develop since it would be difficult to accurately determine exactly what they knew before teaching. The second questions focuses on the engineering pedagogical content knowledge the teachers both use and develop. In the case of engineering pedagogical content knowledge the assumption is that the teachers, having never taught engineering, will be developing what they use as pedagogical content knowledge. This coincides with the literature and research that describe

pedagogical content knowledge as being developed during the course of teaching (Driel, Verloop, & Vos, 1998; Veal, Tippins, & Bell, 1998).

The teachers selected for this study were all teaching the same curriculum, and teaching it for the first time. The researcher recruited these teachers from a professional development workshop he helped develop and lead. The researcher developed the curriculum with assistance from colleagues at the Tufts' University Center for Engineering Educational Outreach (CEEEO), TechBoston (a division of the Boston Public Schools), and Northeastern University, to incorporate middle-school engineering principles into a LEGO robotics engineering design challenge. The researcher, along with TechBoston and Northeastern University collaborators, led a two-week professional development workshop in the summer of 2006 where 25 Massachusetts teachers, including those recruited for participating in the study, spent one week learning a LEGO-robotics engineering curriculum and the second week teaching the curriculum in a practicum. Three teachers were then recruited to participate in this research study, where they would be interviewed and observed in their after-school classrooms to identify the subject matter knowledge and pedagogical content knowledge used and developed to teach engineering.

After-school Setting

The curriculum was originally designed for use in an after-school setting, as there was not yet district approval to teach engineering during the school day. The after-school setting is different from the school day setting in several ways. Most notably, in the after-school setting there are fewer students, approximately ten as opposed to twenty or more. The teachers and students do not have as much "at stake" in teaching and learning the topics of the after-school curriculum (i.e., they will not be tested on the subject matter). Lastly, the atmosphere of the after-school setting is more relaxed and both the students and the teachers see it as a time for less

rigor and rules. These are some of the disadvantages of conducting research in an after-school setting and may lead to results that are not typical to the traditional classroom. However, for this research in particular, looking at teacher knowledge, the after-school setting still requires the teacher to be able to present new ideas to the students and then work with them as they design their final projects. Researching the teacher's subject matter knowledge and pedagogical content knowledge will still be possible. The smaller class size may also be a benefit in this research as the teacher would not be as likely to be overwhelmed with the chaotic nature of teaching engineering design tasks, which can be teacher-intensive. Ideally, in the future, this research would be conducted in a traditional classroom study; however, for the purpose of this study the after-school setting will provide an adequate window to observe teachers' knowledge.

The Curriculum

The engineering curriculum developed by the researcher and colleagues at TechBoston and Northeastern University was designed to give the students an opportunity to learn some basic engineering principles and the engineering design process and then apply what they learned in an open-ended design challenge. The Massachusetts state curriculum frameworks for science and technology guided the curriculum development. Several standards from the technology and engineering portion of the frameworks were incorporated in to the various lessons (see Table 3). The curriculum team, which consisted of the researcher, a technology education specialist, engineering professors, an educational psychologist, and an education professor wanted to create a curriculum that would be hands-on and exciting for the students and also address academic standards the students are tested on in their Massachusetts Comprehensive Assessments (MCAS). The team believed the engineering design process should be the central topic of the curriculum, as it is at the core of all the engineering disciplines. The curriculum team did not

intentionally choose to address any specific math or science content with the curriculum, but did realize there would be many math and science concepts that teachers could address throughout. The curriculum consists of 11 lessons (see Table 4) that take approximately 15 hours to teach (each lesson is approximately 1.5 hours long). A sample lesson is included in Appendix A. The first half of the lessons were tasks or challenges where student teams practiced using the LEGO robotics toolset and/or ROBOLAB programming language to begin to learn and understand concepts of engineering design, redesign, gears, structural engineering, communication systems, and programming. In the second half of the lessons, the student teams then applied the engineering design process to a final project where they had to design, build, and program an assistive device using the LEGO robotics toolset. The curriculum team chose creating an assistive device as a final project as it addressed one of the state educational standards (Massachusetts DOE, 2006) and was considered to appeal to female students who are often “turned off” by engineering based on research showing female students’ interest in health and human related sciences (Haussler & Hoffman, 2002; Mann, 1994; Stadler, Duit, & Benkes, 2000).

Table 2: Robotics Unit Outline

Lesson(s)	Title: Description	Subject matter knowledge potentially addressed
0	Introduction to Engineering Design Process: The objective of this lesson is to provide students with an opportunity to use the Engineering Design Process (EDP) to solve a simple problem before having it explicitly described and applied to more complex problems.	Engineering design process Force Torque/Bending Moment Symmetry Graphing Percentage
1	Form Companies/Select a Solution: The objective of this lesson is to have the students work on the first few steps of the engineering design process (identify the need, research the need, select a solution) in more detail.	Engineering design process Design constraints Tradeoffs
2	Wheelchair Design Challenge: Students will begin to work with the Engineering Design Process as they build a wheelchair within certain constraints.	Engineering design process Design constraints Forces/statics Symmetry
3	Introduction to Gears and Orthographic Drawings: The objective of this lesson is to introduce the students to how gears work so they can use them in their final projects. The students will also be introduced to orthographic and isometric drawings in this lesson.	Engineering design process Transportation systems Tradeoffs Gears (torque, speed) Force and motion Simple machines Ratios, scale, measurement
4	Begin Final Project – Identify Need, Research Problem, and Develop Solutions: The objective of this lesson is to have the student companies identify and select a need or problem that they will address with their final project. The companies will then research the need or problem and start to develop possible solutions.	Engineering design process Design constraints
5-6	Programming with ROBOLAB: The objectives of these lessons are to introduce the students to the ROBOLAB programming language. They should start to develop the terminology and basics of computer programming. These lessons will give them a foundation for future programming for this unit	Communication systems Sensors Electronics Computer programming
7-10	Lesson 7-10: Final Projects – Working Through the Engineering Design Process: The objective of the final project is to have the students work through the entire engineering design process to design and build an assistive device out of LEGO.	Application of all of the above

The curriculum team, along with experienced middle-school teachers, tested and redesigned the curriculum over a two-year period to its current state. The LEGO robotics toolset—LEGO MINDSTORMS robotics sets and ROBOLAB programming language—that the students use in

the curriculum has been used in middle-school classrooms since 1998 (Portsmore, 1999). The LEGO toolset allows students to quickly create prototypes, test them, and redesign them, which is not afforded by many other types of construction media. The LEGO robotics set lets students quickly create motorized projects that use sensors for control and feedback. The programming language, ROBOLAB, allows students to program their robotic artifacts with little or no prior programming or electronics knowledge.

Study Participants

The three Massachusetts middle-school teachers who participated in this study were all teaching the LEGO robotics/engineering unit previously developed by the researcher. The teachers were selected from the group of 25 teachers that participated in the aforementioned summer professional development workshop. Teachers were recruited from the Boston Public School system and Boston Metro schools to participate in the summer workshop. Initially, four teachers (Caitlin, Michael, Blaine, and Ken – pseudonyms used in place of real names) were chosen due to the proximity of their schools to the researcher and the timing of their afterschool sessions. One teacher, Ken, was unable to complete teaching the unit with his students and was dropped from the remainder of the study. A brief description of the remaining teachers follows.

Caitlin (2nd year, 6th grade math teacher)

Caitlin, a sixth-grade math teacher, was in her second year of teaching within the Boston Public School system. She received a Bachelor's degree in math and received her Master's degree in teaching and began teaching upon graduation. Caitlin enrolled in the summer professional development workshop upon the recommendation of the teacher whom she was replacing at her school. This teacher had been doing LEGO robotics and engineering in the

classroom and afterschool for 5+ years. She did not want the program to disappear and encouraged Caitlin to take it over. Caitlin was excited about the opportunity and took the summer workshop to begin to get familiar with the LEGO robotics toolset and engineering. Caitlin did have some prior engineering experience. She attended a high school that focused on math, science, and engineering. Caitlin described the one engineering course she took as a hands-on, project-based course where the class went through the entire engineering design process to design and build some sort of product. She also explained that many of the math and science courses she took were often linked to engineering or engineering problems. Caitlin was not very familiar with the LEGO robotics toolset and had never used or played with the robotic portions (motors, microcomputer) of the toolset.

Michael (2nd year, 8th grade math teacher)

Michael, an eighth-grade math teacher, was in his second year teaching in the Boston Public School system. He took a slightly different, less traditional route to becoming a math teacher. Michael earned his Bachelor's degree in computer science. He was unsuccessful in finding a computer programming job out of college and he found himself substitute teaching often. He enjoyed teaching and began a teaching leadership program through the Boston Public Schools to become a math teacher. During this time, Michael started an afterschool robotics club with materials that had been left behind by a retired teacher. Michael said he relied on his computer programming background and extensive experience building with LEGO as a child to lead the club. He admitted that he was not very familiar with the motorized components of the LEGO toolset and was learning as he went. He attended the summer workshop to learn how to teach a curriculum based on the LEGO toolset as well as how to design lessons and curricula

using the toolset. In college, Michael took a handful of software engineering courses; however, he expressed in an interview that none of these courses challenged him to create one large piece of software and go through an entire engineering design process. Instead, the courses focused on small, focused projects that were intended to apply theory and programming they were learning in the class. Michael also considered working with his uncle on various building projects around the house as engineering experience that helped form his knowledge base of engineering.

Blaine (14th year, 6th-8th grade science teacher)

Blaine, a sixth, seventh, and eighth-grade science teacher, was in his 14th year of teaching. Blaine taught elementary science for four years and has been teaching middle-school science for the past ten years in the Newton Public School system. He received his Bachelor's degree in International Relations, but did considerable science coursework before he switched to a major in International Relations from a major in wildlife biology. After graduating from college, Blaine joined the Peace Corps for two years where he fixed and maintained water sanitation pumps and later trained others to do this, something he described as highly related to engineering. He later received a Master's degree in teaching and began teaching science. Blaine also noted that he had addressed some of the engineering standards as detailed in the Massachusetts DOE Science and Technology frameworks. He taught lessons where students designed and built windmills and solar cars with his students. He also had a senior mechanical engineering student from a local college assist him in teaching some of this engineering content one year. Blaine did not have any experience with the LEGO robotics toolset and was new to both the robotic building and programming.

Role of the Researcher

The researcher conducting the study reported in this paper plays a number of key roles for the teachers in the study. The researcher is a doctoral student studying engineering education at Tufts University. He has a Bachelor's degree in mechanical engineering, three years experience working as a mechanical engineer, and was in his third year of the doctoral program in engineering education while conducting the study. The researcher was the lead instructor for the teachers during their 2-week summer professional development program. He delivered the entire curriculum to the teachers and worked with them on their LEGO designs. He also led instruction on more advanced engineering principles that were not included in the curriculum for the students. This established a relationship where the teachers may have viewed the researcher as an expert in engineering and LEGO building and design. The researcher also conducted all the classroom observations and interviews. During classroom observations, the researcher was available as a resource to the teachers.

Data Collection

A minimum of two interviews with the teachers, during and after teaching the engineering unit, combined with a minimum of three classroom observations of the teachers teaching in the classroom comprised the data collected for the study. These two methods of data collection allowed for the teachers to both verbalize what they were doing and experiencing, and allowed the researcher to confirm and see what the teachers were doing in the classroom. Using these two methods of data collection—interviews and observations—also allowed for triangulation as a method to confirm and strengthen the data analysis. The observations could be further supported by the teachers' responses and vice versa.

The interviews took place either in the classroom shortly after the day's session, over the phone during a convenient time for the teacher, or during an afternoon when the student session was cancelled. The interviews were done using a semi-structured approach. Each interview was recorded and transcribed. The initial interviews were structured to inquire into the educational and experiential background of the teachers. The interviews elicited the undergraduate and graduate degrees attained, major content areas studied, and continuing education courses taken by these teachers, as a way to understand their subject matter knowledge in math and/or science and engineering. They also included questions regarding less formal experiential education that may have contributed to their engineering subject matter knowledge. Later interviews were structured to examine classroom events and the subject matter knowledge and pedagogical content knowledge the teacher drew upon throughout the lesson. Final interviews were designed to allow the teacher to reflect upon their progress in teaching the engineering unit, describe what and how they learned, and project how they would or could do things in the future. Each of the interviews had questions focused on the teachers' knowledge bases for teaching engineering (physics, math, engineering, and LEGO subject matter, and pedagogical content knowledge).

Classroom observations were conducted at different times for each teacher throughout the course of the unit. Although identical lessons were not observed for each teacher, the observations did capture at least one of the more structured lessons that took place near the beginning of the unit, and at least two of the less structured lessons at the end of the unit where the teachers were working with their students as they built their final projects. The researcher recognizes that the ideal situation would have been to observe all classroom sessions; however, scheduling limitations did not allow this. The researcher believed capturing the teachers in a structured lesson and in unstructured project lessons would be adequate to begin gathering

teacher knowledge data for the purposes of this pilot study. During the class sessions, the researcher attempted to stay in the background and be as unobtrusive as possible. The observations captured the teachers' strategies or techniques, their knowledge of the content, their difficulties or challenges, and the complexity of their students' final projects.

Data analysis

Approach

Miles and Huberman's (1994) qualitative data analysis approach was applied in the analysis of the interview and observation data. The approach incorporates numerous types of data into displays and matrices to help reduce and organize data for easy analysis. Then the data is analyzed by, for example, noting patterns and themes, clustering data, making comparisons, and noting relationships. New coding schemes are then defined and applied to further organize and reduce the data into conceptually ordered matrices and charts. These matrices and charts are then analyzed. Both within-case analysis for each teacher and cross-case analysis among the three teachers were used to examine the data. The next section, *Coding*, defines and describes the codes used to reduce and organize the data into a descriptive matrix for each teacher. The *Results* section defines and describes new codes and displays developed as the analysis progressed.

Coding

The research questions—*What subject matter knowledge do middle-school math and science teachers draw upon as they teach an engineering unit? What engineering pedagogical content knowledge are middle-school math and science teachers using and developing as they*

teach an engineering unit?—guiding this study consist of constructs within the knowledge base of teaching, namely, subject matter knowledge and pedagogical content knowledge. A review of the literature of these constructs served as a foundation to conduct a domain analysis as described by Spradley (1980), where subject matter knowledge and pedagogical content knowledge could be broken down into more detailed types of knowledge. From the first research question, it was clear that each instance of a teacher displaying knowledge of math, science, or engineering would be important to capture for analysis. To highlight these incidences and reduce the data, the following codes were developed for the initial pass through the data.

- SSK – Science subject matter knowledge. Instances where the informant correctly or incorrectly uses or refers to science knowledge. Instances where the observer witnesses use of science knowledge either in a classroom event or spoken during an interview. For example, the teacher recognizes the lever arm on the mechanism is too long and the weight on the end is creating so much torque the motor cannot turn the arm.
- MSK – Math subject matter knowledge. Instances where the informant correctly or incorrectly uses or refers to math knowledge. Instances where the observer witnesses use of math knowledge either in a classroom event or spoken during an interview. For example, the teacher recognizes that the student wants to reduce the speed of their geared mechanism by $1/3$ and talks about the mathematical ratios involved in the device's gears.
- ESK – Engineering subject matter knowledge. Instances where the informant correctly or incorrectly uses or refers to engineering knowledge. Instances where the observer witnesses use of engineering knowledge either in a classroom event or

spoken during an interview. For example, the teacher talks to a student about the tradeoffs and design decisions they are making with their device.

The second research question requires instances of the teachers' pedagogical content knowledge to be captured for analysis. The following codes were derived from a review of the pedagogical content knowledge literature and the focus from the research question to capture what is being both used and developed.

- PCK(KS)-Pedagogical content knowledge (knowing students). Instances where the informant describes or the observer witnesses his or her knowledge of what misconceptions students have about engineering, what engineering concepts they struggle with, how they are unique, etc. For example, the teacher recognizes that the students have a difficult time considering more than three design criteria at once.
- PCK(RWE)-Pedagogical content knowledge (real-world examples). Instances where the informant describes or the observer witnesses real world engineering examples he or she uses to link what is being taught in the lesson to examples the students can relate to. For example, the teacher asks a student how a bike's gearing helps them go up hills easier and relates that to incorporating a LEGO gear into their device.
- PCK(AE)- Pedagogical content knowledge (appropriate examples). Instances where the informant describes or the observer witnesses engineering examples he or she uses that are appropriate for specific children or learning styles. For example, the teacher recognizes that a free-body diagram of multiple objects and forces is too complex for the student and uses a simpler example using just one object and related forces.

- PCK(LM)-Pedagogical content knowledge (lesson management). Instances where the informant describes or the observer witnesses his or her methods of managing the lesson that are specific to the content (engineering) being taught. For example, the teacher recognizes that the idea generation phase of a particular design challenge will likely take more time than usual and allots 10 more minutes.
- PCK(SU)- Pedagogical content knowledge (strategies for student understanding). Instances where the informant describes or the observer witnesses strategies he or she uses to help foster and deepen the students' understanding of the engineering material. For example, the teacher relates the concept of circumference that a student is learning in math class that week to how gear ratios relate to each other.

Along with these codes, the interviews and observations were organized into teaching obstacles. Each time a student needed assistance with their design and the teacher did not immediately have a solution, this was recorded as an obstacle. For each obstacle, the following were recorded: the strategy the teacher used to overcome the obstacle; the outcome; and the concept or issue involved in the obstacle. Figure 2, below, shows an example of an obstacle and how it would be recorded. These obstacles could then be analyzed to deduce the behavior, as described by Piaget (Gruber & Voneche, 1977), the teachers display when faced with an incident challenging their knowledge. Do the teachers see the incident as a simple annoyance and just try again not really taking anything new into account (*alpha-behavior*); do they take the incident into account and attempt to use previously accepted ideas to overcome the incident (*beta-behavior*); or do they understand that the incident is just another complexity of the system and can integrate it with their overall understanding of the system (*gamma-behavior*)? The teachers' strategy to overcome

the obstacle could also be mapped onto Piaget's (Gruber & Voneche, 1977) process of equilibration where the teachers assimilate and accommodate new knowledge.

Date	Obstacle	Strategy to overcome	Outcome	Math, Science, and/or Engineering Concept
01/01/07	Student's car will not drive straight and veers to the left	Teacher studied the student's car. Does not see an immediate problem. Looks at other students' cars and looks again at first car. Notices a slight difference. Asks the student to look at the two cars to see if he sees a difference. Teacher does not point it out right away. Student does not see the difference. Teacher asks the student to look at the left wheels on both cars. The student then sees the difference, and says that the friction must be slowing the left wheel down and that is why it is turning to the left.	Success. Teacher and student both understand the issue and how to resolve it.	Friction, symmetry

Figure 2: Example Obstacle Coding

Results

In this section, I will present and discuss the data compiled from all the interviews and observations of the teachers as they taught the engineering unit. The results are first broken down into sections for each teacher presenting the subject matter knowledge they used, the pedagogical content knowledge they used, the assessment of their students' projects, and the obstacles they encountered while teaching the curriculum. This organization allows each teacher's case to be completely laid out. Later, in the *Discussion* section of this paper, the teachers' results are compared and contrasted.

Michael (2nd year, 8th grade math teacher)

Michael taught the engineering curriculum in an afterschool program with nine eighth-grade students. He formed four groups with two students each and one student chose to work on their own. This lone student spent most of the time working on a personal project not connected to the curriculum. Michael assigned the groups and had three mixed-gender dyads (1 female and 1 male) and one all-male dyad. He created the groups such that no one person would dominate the building process. He noticed from the first few lessons of the curriculum which students had more “dominant personalities” and tried to match them with other “dominant personalities” for working on the final projects because he wanted the students to get equal time in the building and creation of their projects (11/20/06 interview). Michael proceeded to teach the lessons following the curriculum quite closely. He chose to skip Lesson 1, and introduction to the design process (see Table 1) because he didn’t think students would be engaged by it (11/20/06 interview). Michael also chose to extend the time for the students to finish their final projects from four one-hour sessions to six one-hour sessions. The researcher conducted eight classroom observations capturing structured lessons 3 and 5 and final six final project sessions. Three of the student groups finished their projects and one was left semi-finished as one group of students missed multiple sessions due to other commitments.

Michael’s Subject Matter Knowledge

Given Michael’s current position as a math teacher and his educational background, it was assumed that he came in with strong middle-school math knowledge. However, he did not appear to rely upon or use his math knowledge very often while teaching the unit. Table 3 includes Michael’s single use of explicit math knowledge that was captured during the classroom observations and interviews. It should be noted that the observations and interviews are not able

to capture all the knowledge Michael uses while he is teaching and he is likely using much more subject matter knowledge and other knowledge while he is teaching.

Table 3. Michael's Math Subject Matter Knowledge

Math Subject Matter Knowledge	
Knowledge Assessment	Evidence (<i>source</i>)
Strong middle-school math knowledge	<ul style="list-style-type: none"> • Certified middle-school math teacher. • Teaches eighth grade algebra. (<i>11/20/06 interview</i>) • Master's degree in math education. (<i>11/20/06 interview</i>)
Used very little math knowledge while teaching the curriculum	<ul style="list-style-type: none"> • Helped student identify why the wheels on the geared wheelchair wouldn't spin (<i>11/16/06 observation</i>). Follow-up interview explained, "I noticed that he [student referred to above] had used the wrong size axles so the back two beams weren't parallel to each other, they were becoming intersecting." (<i>11/20/06 interview</i>) • This was the only instance of math subject matter knowledge recorded in observations or interviews.

The observations revealed that Michael used little science knowledge teaching the curriculum. The interviews allowed Michael to express that science and physics are one of his main weaknesses in teaching the engineering curriculum (see Table 4). This limitation may explain why Michael was not observed accurately linking any science concepts to the design task at hand. He did attempt to link the concept of friction on one occasion, but incorrectly referred to it as tension, as can be seen in Table 4. Considering that Michael's background is in math and computer science, it is not a surprise that he may lack some of the basic physics knowledge that is necessary in analyzing robotic devices. How much physics knowledge Michael would need is unclear, but as he admits, this is knowledge that could help him highlight concepts at play in the students' designs.

Table 4. Michael's Science Subject Matter Knowledge

Science Subject Matter Knowledge	
Knowledge Assessment	Evidence (<i>source</i>)
Middle-school science/physics knowledge – self-described as a weakness	<ul style="list-style-type: none"> • “Another weakness [of mine] was sometimes students would ask how you do this and I didn’t know the physics behind it... a weakness ... figure out how to improve it like what physics or engineering would make it better.” (5/9/07 <i>interview</i>) • Used term tension instead of friction when talking about a car’s wheels providing resistance for turning. (3/7/07 <i>observation</i>)
Used no accurate science knowledge explicitly	<ul style="list-style-type: none"> • Used term tension instead of friction when talking about a car’s wheels providing resistance for turning. (3/7/07 <i>observation</i>) • No other observed uses of specific science concepts.

Michael did use engineering subject matter knowledge. He displayed strong troubleshooting and analysis skills while working with students and their designs. Table 4 provides a few examples of this knowledge. One potential source for this knowledge was the prior LEGO knowledge Michael had. In Michael’s first interview (11/20/06) he stated that he grew up playing with LEGO and had previously led an afterschool club that used LEGO robotics. This familiarity with the materials may have greatly assisted him in identifying problems and solutions with his students. The systematic approach he displayed with his students while troubleshooting may also be a result of his computer science education, where a systematic approach to problem solving and algorithm development are a focus (Gibbs & Tucker, 1986). The computer science background also appeared to be very valuable when it came to the programming aspect of the robotics. Michael was well versed in the programming terminology.

Table 5. Michael's Engineering Subject Matter Knowledge

Engineering Subject Matter Knowledge	
Knowledge Assessment	Evidence (source)
Strong troubleshooting and analysis knowledge with engineering design process	<ul style="list-style-type: none"> • Notices a student's design is not square/symmetric and explains potential "engineering" problems. (1/31/07 observation) • Interaction with student doing wheelchair drop. Asks why it is strong, why he chose tires, drops it and it succeeds multiple times. Drops on side and it breaks into two pieces. Teacher asks how he could strengthen the two pieces. Teacher shows other students' strong designs. Student redesigns a couple of times and explains to teacher why it worked. Illustrates troubleshooting process with student. (2/8/07 observation)
Moderate and emerging engineering content knowledge	<ul style="list-style-type: none"> • <i>Computer programming</i> <ul style="list-style-type: none"> ○ Computer science Bachelor's degree. (11/20/06 interview) ○ Demonstrates knowledge of DO and WHILE loops and FORKS. (11/20/06 interview) • <i>Gears/Pulleys</i> <ul style="list-style-type: none"> ○ Introduces gears to students and elaborates (beyond what was provided in the teacher resources) on how they work on bikes. Creates a physical demo of a gear train to show students how the torque is increased with the gear ratio. Uses correct terminology and is accurate with all information presented on gears. (11/16/06 observation) ○ Asks researcher how pulleys work (whether they work like gear ratios). Researcher says yes and Michael continues to work with student to implement pulleys. (3/7/07 observation)

Michael's Pedagogical Content Knowledge

The following tables (see Tables 6, 7, 8) illustrate the pedagogical content knowledge Michael displayed throughout teaching the engineering curriculum. The pedagogical content knowledge focused on here includes: *knowing students*, *strategies for student understanding*, and *real-world examples*. The other categories of pedagogical content knowledge (*appropriate examples* and *lesson management*) are not included in this discussion because there was not sufficient data collected on this knowledge. Michael showed he had solid *knowledge of his students*. He had some idea of what knowledge his students came in with regarding building with LEGO and to what extent they could handle complex problems from his previous experience running a robotics club (see Table 6). Michael also had an excellent rapport with his students and

good knowledge of what kinds of things they were interested in. This knowledge of his students appeared to assist Michael in peaking the students' interests with the engineering curriculum and led to a classroom environment where the students enjoyed working on their projects based on the researcher's experience of the students and learning environment (11/29/06 observation).

Table 6. Michael's Knowledge of Students

Pedagogical Content Knowledge – Knowing Students (KS)	
Knowledge Assessment	Evidence (source)
Had some knowledge of students' prior knowledge	<ul style="list-style-type: none"> • Students in his previous robotics club “weren’t capable... didn’t know how to build [LEGO]” coming in. (11/20/06 interview) • Some students couldn’t handle too many steps at once, “like too many tasks, like in-depth math problems that take four steps, half the students would get lost.” (3/29/07 interview) • Students would benefit from having “a basic idea of how simple machines work or in design of simple machines” (2/28/07 interview)
Developed a rapport with the students and had an understanding of their interests	<ul style="list-style-type: none"> • “I didn’t know if the students would be engaged by it [Lesson 1]” so I skipped the lesson. (11/20/06 interview) • Came up with real-world examples that related to the students’ interests. (see Table 8) • Understood student’s concern for working without her partner on something they had been developing together and had her work on something that she was interested in improving. (2/28/07 interview) • Grouped students based on “dominant” personalities so students would get equal time building the projects. (11/26/06 interview)

Under the category of *strategies for student understanding (SU)*, Michael primarily used inquiry techniques to empower the students to come up with their own answers. Michael stated early on that he learned it was best not to fix the students' problems:

Michael: I think when I first taught it [LEGO robotics], I was quick to take it [their LEGO project] away from them and fix it for them. I think I will probably always have to stop myself from doing that. (11/20/06 interview)

Michael consistently inquired into possible solutions with students when they had questions or issues that arose with their designs. Michael also had students who had figured something out on their own show other students who were struggling with the same issue.

Table 7. Michael's Strategies for Student Understanding

Pedagogical Content Knowledge – Strategies for Student Understanding (SU)	
Knowledge Assessment	Evidence (<i>source</i>)
Inquires and discusses with students to have them find their own answers	<ul style="list-style-type: none"> • Asks students to elaborate on their questions and they begin to answer their own questions. (2/8/07 <i>observation</i>) • Worked with student to troubleshoot design. “So I held it up to him [student] and asked him what is wrong with this?” (11/20/06 <i>interview</i>) • Working with student asks what she wants to happen, she doesn’t know, asks her to imagine she was going to use device and what she would want to have happen. (3/7/07 <i>observation</i>)
Empowers students to share their knowledge and teach classmates	<ul style="list-style-type: none"> • Has student who figured out how to connect motor to wheelchair show other students how to do it. (11/16/06 <i>observation</i>) • Has one student show another student how they made the doors move in their project. (1/31/07 <i>observation</i>) • After testing wheelchairs has student point out what made their designs strong or weak. (2/8/07 <i>observation</i>)

Another strength of Michael’s teaching of the unit was the *real-world examples* he developed on the spot to help students better understand the concept at hand. He would relate concepts students were not quite grasping to video games they played or would give them a physical demonstration where they could experience the concept. Michael’s use of real-world examples also revealed the excellent rapport he had with his students. He consistently came up with examples that both he and his students could relate to.

Table 8. Michael's Use of Real-world Examples

Pedagogical Content Knowledge – Real-world Examples (RWE)	
Knowledge Assessment	Evidence (<i>source</i>)
Consistently uses real-world examples that students can relate to	<ul style="list-style-type: none"> • Relates making tradeoffs in design to racing video game where you trade off handling for speed. (<i>11/29/06 observation</i>) • Relates saving programs on LEGO microcontroller to saving games on computer game Warcraft after asking student what computer games he played. (<i>11/29/06 observation</i>) • Built hands-on gear demo for students to feel the difference in torque. (<i>11/16/06 observation</i>)

Obstacles Michael Faced While Teaching the Unit

Throughout teaching the unit, Michael ran into obstacles, where he was, at first, unclear about how to answer the students' questions or solve a problem. This is a common challenge that arises out of an open-ended project (Edelson, Gordin, & Pea, 1999). When Michael encountered such an obstacle, his approach, knowledge used (both subject matter and pedagogical content) and outcome were observed and recorded, as outlined in the *Coding* section of this paper. The following section reveals how Michael deals with two such obstacles and the knowledge he calls upon to overcome them. These two obstacles were the more salient examples the researcher was able to capture in Michael's teaching.

Troubleshooting: a systematic approach.

In this obstacle, one of Michael's students, while building a geared up car as part of one of the directed lessons, could not figure out why his wheels would not spin freely like the other students' designs. Here is the transcript of Michael describing the incident:

Michael: As a teacher, I went back to my own experience in that same investigation that we did, and I was thinking that, at first, it couldn't spin because it had too many gears

going back and forth. It would be spinning really fast if you spun the wheel versus if you spun the motor it would spin slowest... that was my first thinking. We would have to hook a motor up to it to see if it worked. Then other students around me were working like zoom zoom zoom. So I was like, "wait a second." After I thought maybe I would let [the student] struggle a bit and have him compare the two and ask what's different with yours.

Researcher: What did you notice was the issue?

Michael: I noticed that he had used the wrong size axles so the back the two beams weren't parallel to each, other they were becoming intersecting. It was squooshing the axles and squooshing the tires together and wouldn't let it spin. So I held it up to him and asked him, "What is wrong with this?" And he said he could see that they were scrunched together and I asked, "What do we need to do?" And he started to pull it apart and then he realized that the axle he had chosen was too small with the wheels on it so he got a bigger axle.

Researcher: What had you pick it up and have him look at it that way?

Michael: Just teacher instinct... he'll remember it more next time if something isn't moving. He'll think maybe it wasn't aligned right. And I offered him that if he put a bigger 2X6 plate on the front and line that up there you will know exactly how far it has to be. I think when I first taught it, I was quick to take it away from them and fix it for

them. I think I will probably always have to stop myself from doing that. (11/20/06 interview)

This example demonstrates Michael's approach to overcoming the obstacle and at least three distinct domains of knowledge Michael employs to solve the problem. First, Michael uses a *systematic troubleshooting approach*. He does not, at first, know what the issue is with the student's design, but has one idea, from past experience, of what might be wrong. He tests that hypothesis and finds that his initial idea was not the issue. He continues with this process, working through one issue or variable at a time until he identifies the issue. This systematic process may closely resemble processes Michael learned and developed in college studying computer science. Mapping this process or approach onto Piaget's described reactions to dealing with perturbations, Michael is likely displaying beta-behavior where he, "seeks to take the perturbation [design problem] into account and to reconcile it with notions and predictions previously accepted" (Gruber & Voneche, 1977, p. 807). This was a behavior he displayed on multiple occasions throughout teaching the unit. Michael's approach also exemplifies Piaget's equilibration process (Gruber & Voneche, 1977). Michael experiences a perturbation (disequilibrium), attempts to apply his prior knowledge and fit it into what he knows (assimilation), and then has to alter his prior conception and adopt a new hypothesis regarding what the issue is (accommodation). It appears that this systematic approach allowed Michael to access his prior knowledge, apply it to the situation, evaluate how well it applies, and repeat the process until the issue is resolved (and he can reach a new level of equilibration). Jonassen and Hung (2006) break troubleshooting into several domains of knowledge or skills: domain knowledge; system/device knowledge; performance/procedural knowledge; strategic knowledge;

experiential knowledge; working memory; causal reasoning; and analytical reasoning. Michael's computer science educational background may very well have helped him develop strategic troubleshooting knowledge, and capacity in causal and analytical reasoning, which could be knowledge and skills used to troubleshoot computer programs. Jonassen and Hung posit that these specific knowledge or skills transfer easily to different applications where the other knowledge and skills are more application specific.

Michael also demonstrates his LEGO building/engineering, math, and pedagogical content knowledge in this example. He is able to examine and identify what the issue was with the design of the LEGO car. Throughout this process, he is referring to prior LEGO building knowledge. His math subject matter knowledge is displayed when he explains that the issue he saw was that the "beams weren't parallel to each other, they were becoming intersecting." He also displayed what may be considered engineering pedagogical content knowledge. In this case, the engineering pedagogical content knowledge is Michael not telling the student what was wrong or how to fix the design, but rather to assist the student to identify the issue on his or her own because that way he or she would remember better next time. Michael does this by holding the car in such a way and directing the student to focus on a particular aspect of the design that would later reveal to the student what the issue was.

Gears.

Michael faced another obstacle when a number of the students were trying to figure out what gear to attach to the motor in order to maximize the advantage of the gear ratio and power [torque] of the car (*11/16/06 observation*). Michael had noticed that one student had figured this out and had a working car. He asked that student to show the other students how to attach the

motors. However, Michael realized that the students were still struggling with the concept of increasing the power [torque] with gears. He decided to make a gear train to demonstrate how the torque is different depending on which end of the gear train you are working with. In the interview following this incident, Michael explained his rationale:

Michael: I thought the demo from the lesson wasn't clear for some students to see it. So I wanted to make something more obvious for them to see, to touch and feel, and grab. It impacted me when [the researcher] asked someone to stop it and they couldn't stop it over the summer [workshop]. So I was trying to do something similar to it that the students could see. *(11/20/06 interview)*

This incident allows Michael to express further engineering pedagogical content knowledge he has developed. He states that the demo from the lesson was not clear for some of the students, which is an example of him knowing whether or not his students are understanding the concept of gears. The strategy he then uses is one where the students get “to see, to touch and feel, and grab” the physical gear demo because Michael believes this had the potential to have more impact on the students. He appears to be applying constructivist pedagogy to the engineering context.

These two examples highlight that Michael does run into obstacles in teaching engineering; however, he is also able to overcome them. Michael’s ability to systematically troubleshoot problems and assess student understanding are a couple of the strengths that help him overcome obstacles in teaching. These strengths relate back to both his subject matter and pedagogical content knowledge. Michael’s computer science background likely helped him

develop strong troubleshooting skills and aided him in teaching the engineering curriculum. Likewise, his pedagogical content knowledge, *knowing students*, also helped Michael overcome these obstacles. Michael's example of overcoming obstacles suggests that an educational background in a field that includes systematic problem solving and troubleshooting may aid a teacher in teaching engineering. His case also highlights the importance of *knowing students* and addressing what they do or do not know with teaching strategies that lead them to *coming to know*, such as guiding the student to identify an issue on their own, and allow the student "to see, touch and feel, and grab" the concept. Michael's case also demonstrates that a teacher does not have to know every concept being applied, but needs to overcome teaching obstacles and successfully guide students by having a way to overcome what he does not know.

Michael Summary

Relating back to the first research question (what subject matter knowledge did Michael use while teaching the engineering unit?), Michael used very little math knowledge, which is likely because the unit itself does not require much math. When Michael did draw upon his math knowledge he did so appropriately and accurately. Michael used very little science or physics knowledge as well. However, this is likely due to Michael's limited educational background and experience in this content area. He also used a substantial amount of knowledge regarding engineering. He has a strong understanding of the engineering design process and how to solve design problems. He used this knowledge often to assist students in their designs. He also used a moderate amount of knowledge regarding concepts such as gears and programming while teaching, and demonstrated he was also developing this knowledge with the assistance of the researcher in the classroom.

Relating to the second research question (what pedagogical content knowledge did Michael use and develop while teaching the engineering unit?), Michael used his strong knowledge of his students, an effective and empowering inquiry approach, and large repertoire of real-world examples. He related very well to his students and did an excellent job in using real-world examples that were interesting for his students. With the knowledge he had of his students, both of their capabilities and interests, he was able to empower them and engage them in inquiry to come to their own answers. When Michael did come across something he did not know or was not sure about, he was able to systematically dissect or troubleshoot the problem and come to a solution. His educational experience as a computer science major may have played a significant role in this.

Caitlin (2nd year, 6th grade math teacher)

Caitlin taught the engineering curriculum in an afterschool program with ten female sixth-grade students. She formed two groups of three students and two groups of two students. Caitlin followed the curriculum quite closely, teaching each of the lessons in the curriculum as designed. Caitlin did add some content on gears in the third lesson that mainly focused on this concept. Caitlin's students had good attendance throughout the sessions and all the groups completed their final projects. On one occasion a few students missed the session. Caitlin chose, in the next session, to redo the lesson with those students and gave the other students a building challenge to work on. The building challenge involved building a mechanism with a sophisticated gear setup, that they called a *Governor rules machine*, using crown and bevel gears. The significance of this decision will become apparent later. The researcher observed the end of structured lesson 2, lessons 3 and 5, and four final project sessions.

Caitlin's Subject Matter Knowledge

Caitlin, like Michael, was assumed to have strong middle-school math subject matter knowledge based on her being a certified middle-school math teacher and having a Bachelor's degree in Mathematics and a Master's degree in teaching. However, also like Michael, Caitlin did not appear to use much of her math knowledge explicitly during the engineering unit. She did use math to help explain gears and gear ratios, but that was the only instance in which she was observed explicitly using math (see Table 9). While Caitlin used math to talk about gears, she did not talk about the science behind gears. In fact, there were no occasions where Caitlin referred explicitly to any science concepts or knowledge (see Table 9).

Table 9. Caitlin's Math Subject Matter Knowledge

Math Subject Matter Knowledge	
Knowledge Assessment	Evidence (source)
Middle-school math knowledge – well-developed (education & experience)	<ul style="list-style-type: none"> • Certified middle-school math teacher. • Teaches sixth grade math. (4/6/07 interview) • Bachelor's and Master's degrees in teaching. (11/17/06 interview)
Used very little math knowledge while teaching the curriculum	<ul style="list-style-type: none"> • “When I was working with my students, I was trying to apply math to them [gears]... like what fraction is a whole turn.” (11/17/06 interview) • This was the only instance of math subject matter knowledge used in observations or interviews.

Table 10. Caitlin's Science Subject Matter Knowledge

Science Subject Matter Knowledge	
Knowledge Assessment	Evidence (source)
Middle-school science/physics knowledge – unclear what students are learning	<ul style="list-style-type: none"> • Did not see the science or physics behind gears. (11/17/06 interview) • Did not know what science her students were learning or what the science curriculum for the district covered. (2/8/07 interview)
Used no science knowledge explicitly	<ul style="list-style-type: none"> • No observed instances of references to specific science concepts.

Caitlin demonstrated a moderate understanding of the engineering design process with her students. Caitlin was able to ask students about their designs and talk about the concept of prototypes, testing and evaluation, and redesign as they worked on their projects. Her experience taking an engineering design class in high school may have impacted this knowledge beyond what she learned in the summer professional development workshop. Caitlin, however, did not demonstrate as much knowledge of engineering concepts as she did of the engineering design process (see Table 11). She had a basic understanding of gears, namely calculating gear ratios and changing speed and torque, but was never very sure of this knowledge and never considered the physics behind gears. When asked if she could benefit from more engineering knowledge, she was unclear as to what she could learn. In other words, she did not know what she did not know regarding engineering. Caitlin also struggled with the ROBOLAB programming and recognized that she could use more training and development with programming.

Table 11. Caitlin's Engineering Subject Matter Knowledge

Engineering Subject Matter Knowledge	
Knowledge Assessment	Evidence (<i>source</i>)
Demonstrated knowledge of the engineering design process	<ul style="list-style-type: none"> • Works with student to analyze their design and asks questions about the necessity of different features and then suggests a redesign. (<i>11/9/06 observation</i>) • Engages students in inquiry about what a prototype is and its purpose. (<i>11/30/06 observation</i>) • Went to a math, science, and engineering high school and took a course where they went through the engineering design process and created a prototype. (<i>11/17/06 interview</i>)
Demonstrated basic knowledge of engineering concepts	<ul style="list-style-type: none"> • Basic understanding of gears. Knew how to find gear ratios, knew changed speed and energy/work, used driver/follower terminology correctly (<i>11/9/06 observation</i>). Seemed unsure of her knowledge of gears, looked at researcher after she realized she was probably wrong with term “gearing up.” (<i>11/9/06 observation</i>) • Did not know how to do some of the programming and emailed an outside resource for assistance and recognized she could use more programming knowledge or training. (<i>2/8/07 interview</i>) • Did not know what kind of engineering knowledge would be useful to learn... just thought she “probably” needed more. (<i>2/8/07 interview</i>) • Explained light sensor as a motion sensor, but seemed unclear about how the sensor actually worked and didn't explain to the students how it worked. (<i>11/30/06 observation</i>)

Caitlin's Pedagogical Content Knowledge

The pedagogical content knowledge captured throughout Caitlin's teaching is displayed in the following tables (see Tables 12, 13, 14). Teaching engineering with LEGO for the first time, Caitlin did not appear to have much pedagogical content knowledge for engineering coming in to this experience, and was actively developing the knowledge. She did not display much *knowledge of her students* and what they knew coming in to the lessons and activities (see Table 12). One hypothesis could be that her lack of background knowledge and experience with engineering concepts limited her in identifying what prior knowledge her students had or would need. For example, she did not know what science her students were learning. However, if she knew the science embedded in the engineering curriculum, maybe she would have been able to discuss the concepts with the science teachers in the school. It also appeared that Caitlin's own

lack of science and engineering knowledge had her not try and elicit her students' science and engineering knowledge. She attempted to provide more content in the curriculum for topics she herself was less confident about (e.g., gears).

Table 12. Caitlin's Knowledge of Students

Pedagogical Content Knowledge – Knowing Students (KS)	
Knowledge Assessment	Evidence (source)
Unsure of students' prior knowledge	<ul style="list-style-type: none"> • “I wasn’t sure what they [students] would know... I went into it without many expectations. I don’t know what they learn in science.” (2/8/07 interview) • “It [geared device] was actually hard for me to make and I thought ‘will my kids be able to make it?’ but they were.” (11/17/06 interview) • “They [students] couldn’t decide which one was the best wheelchair... that was a little [surprising].” (11/17/06 interview)
Based students' science and engineering knowledge on her own science and engineering knowledge	<ul style="list-style-type: none"> • “It seems like my students, and they’re all female, didn’t know much about engineering or what is was.” (11/17/06 interview) • “I felt like I had to add a little more about gears so they could understand it.” (11/17/06 interview) Later surprised with students’ ability to build geared device, “It [geared device] was actually hard for me to make and I thought ‘will my kids be able to make it?’ but they were.” (11/17/06 interview) Later, when asked if the students were more competent or confident around gears, “Oh yeah, gears. I didn’t really come back to gears so probably not.” (2/8/07 interview)

Caitlin’s *strategies to strengthen students’ understanding* were balanced between an inquiry approach and a more instructional or directed approach. It appeared that Caitlin probed students and helped guide them to find their own answers when working with the engineering design process, something she was competent with. She would resort to a more directed approach with concepts she was less competent with such as programming and gears. Maybe Caitlin will take a more inquiry-based approach as she develops her knowledge of programming and gears.

Table 13: Caitlin's Strategies for Student Understanding

Pedagogical Content Knowledge – Strategies for Student Understanding (SU)	
Knowledge Assessment	Evidence (source)
Uses classroom argumentation to have students find their own answers	<ul style="list-style-type: none"> Asks students where wheelchairs broke in drop test and then asks how they could improve it. Asks them to elaborate when they say make it stronger. (11/9/06 observation) Inquires into what a prototype is with students. (11/30/06 interview)
Gives formal, directed instructions or suggestions	<ul style="list-style-type: none"> Teaches programming in a very directed way (e.g. open this, wire this, etc.). (12/14/06 observation) Lecture style presentation on gears up front on board. (11/16/06 observation) Has students work on a gear worksheet. (11/9/06 observation) “I prodded them saying you could knock them in,” when assisting students with figuring out how to make a robot move books. (2/8/07 interview)

Caitlin’s use of *real-world examples* demonstrated that she did have a certain amount of knowledge of what her students were interested in. The students were able to relate to Caitlin’s analogy of buying a cell phone (11/16/06 observation), and Caitlin stated that she wanted to relate the content to her students as much as she could (11/17/06 interview).

Table 14. Caitlin's Use of Real-world Examples

Pedagogical Content Knowledge – Real-world Examples (RWE)	
Knowledge Assessment	Evidence (source)
Uses real-world examples that relate to the students’ lives	<ul style="list-style-type: none"> Related trade-offs and design decisions to buying a cell phone. (11/17/06 interview) “I feel I have to relate it to them more so I try and think of stuff [real-world examples] on the spot.” (11/17/06 interview) Shows her assistive device from her summer workshop as an example for her students (11/30/06 observation). Regarding future possibilities, she mentioned, “I’d probably show them more examples of things other people built,” to help them think outside the box in terms of creating their assistive device. (2/8/07 observation)

Obstacles Caitlin Faced While Teaching the Unit

Throughout teaching the unit, Caitlin ran into obstacles, where she did not know what to do instantly. These obstacles were observed and recorded as outlined in the *Coding* section of

this paper. The most pervasive obstacle that Caitlin ran into concerned the concept of gears. The following section summarizes Caitlin's ongoing obstacle with teaching the concept of gears.

Gears.

The most salient obstacle throughout the curriculum for Caitlin was the concept of gears. Caitlin thought that gears would be important for her students to understand as they built their devices. She stated that, "gears were kind of important at least in thinking about how things work. I felt that I had to add a little more about gears so they could understand" (11/17/06 *interview*). Caitlin was clear about the importance of gears, but was also unsure about her own knowledge of gears. In the classroom, Caitlin often looked unsure of herself when she explained gears. She also looked to the researcher for approval a few times to make sure that what she was saying was correct. The following exchange from an interview following a session highlights Caitlin's views of her knowledge of gears:

Researcher: How comfortable are you with your knowledge of gears?

Caitlin: Umm... (laughs) My knowledge of gears is what I presented to them... yeah.

Researcher: Where did you get most of the knowledge you have about gears?

Caitlin: Well, I think I must have learned about gears at some point, but I forgot. Just trying to figure out how it works and then looking online and trying to figure out how it works. And the gear ratios and stuff, I just tried to figure out in my head.

Researcher: When you were trying to figure the gears out, were you using more physics or math?

Caitlin: I guess both, but when I was asking the kids, “When one smaller gear turns one full rotation, how much does the larger gear turn?” So the larger one would only turn a fraction. So, when I was working with my students I was trying to apply math and fractions to them... like, “What fraction of a whole turn?” So I think mostly math... and not so much physics. (*11/17/06 interview*)

This exchange, along with observations of her looking to the researcher for affirmation while presenting gears to her students (*11/6/06 observation*), show that Caitlin is unsure about her own knowledge of gears and lacks confidence with the topic. Later in the curriculum, when the students were building their final projects, one student asked Caitlin how she could make the arm on the wheelchair move up and down to raise and lower a television. Caitlin knew the student needed to use a motor and gears, but did not quite know how (*1/25/07 observation*). As Caitlin was exploring with the student how to do this, the student grabbed one of the earlier projects they had made, *The governor rules machine*, and showed Caitlin to see if this would help. Caitlin continued to struggle with how to transfer what was going on in *The governor rules machine* to what the student wanted to do. Caitlin, eventually, looked over to the researcher and asked how he would approach this. The researcher gave the student a few possible solutions that the student used to make the arm move up and down.

This interaction also reveals that Caitlin was using her math knowledge when working with gears. In the classroom, she was clear and precise about calculating gear ratios and appeared

comfortable when presenting that to her students. However, the math of calculating gear ratios does not include knowledge about the physics behind gears and how they create a mechanical advantage, which is knowledge Caitlin appeared to lack. Having this physics knowledge may have helped her make connections to incorporate gears in her teaching. Of Caitlin's students, only two of the four teams used gears or any sort of mechanical advantage in their designs (see Appendix B for student project assessments). The two teams that did use gears used them in very simple ways—connecting a gear to the motor to raise and lower an arm—and one of those two teams was assisted by the researcher in the classroom. Caitlin's perturbation with gears reveals her behavior for dealing with this perturbation. It is not necessarily clear cut in this case, but it appears Caitlin exhibits an alpha-behavior as described by Piaget (1975/1977). An alpha-behavior is described as an attempt to cancel the perturbation without taking it into account and trying to resolve it with other knowledge, or, in other words, pushing forward without addressing previous concerns. Caitlin does not appear to recognize or try to account for the concepts of gears beyond applying gear ratios (math) to the change of speed and torque. When knowledge beyond this is required she was unable to move beyond it, and, on one occasion, deferred to the researcher.

In Caitlin's case, her challenge to overcome the obstacle of teaching gears may suggest that an engineering concept like gears, in the case of this curriculum, should be developed with teachers who have little experience with it. Caitlin likely would have benefited from more conceptual knowledge regarding gears and engineering in general. It is not to say a math major could not teach engineering or gears, but that additional development or experience may aid them in teaching such a curriculum.

Caitlin Summary

What subject matter knowledge did Caitlin use while teaching the engineering unit? She used very little math knowledge explicitly, very little physics or science knowledge, and used a moderate amount of engineering knowledge. The engineering unit did not require Caitlin to use much math knowledge; however, when she did use math knowledge to discuss gears, she did so accurately. Caitlin's physics knowledge may have restricted her teaching as she struggled in her explanations in having her students implement gears into their designs. She was also not familiar with the science her students had learned or were learning, which could have allowed her to make the connections between what they had already learned and their designs. Caitlin did use knowledge of the engineering design process and was able to engage her students in inquiries about the process. It is possible that her experience taking a high school engineering design course contributed to this knowledge. However, Caitlin did not demonstrate similar knowledge of engineering concepts, which may correspond with her physics or science knowledge. There is no way to determine, from the data gathered, whether or not Caitlin was using more math, science, or engineering knowledge beyond what she verbally stated to the researcher in the interviews or to her students within the observations.

The second research question seeks to answer what pedagogical content knowledge Caitlin used and developed teaching the engineering unit. Caitlin did not know much about her students' prior knowledge. She was unclear on what they already knew about science and engineering and at times was surprised by what they did or did not know. Caitlin may not have been comfortable or familiar with her own science and engineering knowledge and was unable to predict or understand what knowledge her students may have had. Caitlin's subject matter knowledge also appeared to play a role in the teaching strategies she used. When she was

knowledgeable with a topic (i.e., the engineering design process), she was more likely to engage her students in an open-ended discussion. However, when she was less knowledgeable (i.e., programming, gears), she resorted to a more instructional or directed teaching approach. Caitlin was able to use some real-world examples when interacting with her students and recognized the importance of developing a cadre of examples to relate to her students.

Blaine (14th year, 6th grade science teacher)

Blaine taught the engineering curriculum in an afterschool program to a group of sixth-grade students. Blaine formed three groups of two—two groups with two male students and one group with two female students. Blaine followed the basic structure of the curriculum, but changed some of the activities. For example, in the session that focused on gears, Blaine added a challenge where the students tried to build the slowest car using gears. Blaine also had a retiree volunteering in the afterschool program with him. The volunteer spent most of his time assisting students with LEGO building. Two of the three groups completed their final project. The group that did not finish did present their idea and how, if they had had more time, they would have finished their project. Blaine said that one student from that group had some out-of-school circumstances that distracted her from working on the project fully, and this was the reason they were unable to completely finish their project. The researcher had scheduling conflicts that resulted in just three classroom observations in Blaine's class. One of these observations was during the structured lesson 5, and two were during the final project building sessions.

Blaine's Subject Matter Knowledge

Blaine came in with a significantly different subject matter knowledge base than Michael or Caitlin. Blaine had strong science subject matter knowledge given his certification to teach middle-school science, fourteen years teaching science, along with the knowledge he demonstrated in interviews (see Table 16). He did use science knowledge regarding simple machines, on one observed occasion, while assisting a student-team come up with some design ideas. Given his depth of knowledge regarding simple machines and the successful implementation of simple machines in his students' projects, Blaine likely used this knowledge on other occasions that were not observed. I was unable to assess his math knowledge because he did not explicitly use math knowledge while teaching nor did he mention it in interviews (see Table 15).

Table 15. Blaine's Math Subject Matter Knowledge

Math Subject Matter Knowledge	
Knowledge Assessment	Evidence (<i>source</i>)
Unable to assess math knowledge	<ul style="list-style-type: none">• No evidence for assessing math subject matter knowledge.
Used no math knowledge while teaching the curriculum	<ul style="list-style-type: none">• No instances of math knowledge used explicitly captured in the interviews or observations.

Table 16. Blaine's Science Subject Matter Knowledge

Science Subject Matter Knowledge	
Knowledge Assessment	Evidence (<i>source</i>)
Strong middle-school science knowledge	<ul style="list-style-type: none"> • Certified science teacher. (<i>12/13/06 observation</i>) • 14 years teaching science (10 middle-school, 4 elementary). (<i>12/13/06 observation</i>) • “The things in the back of my mind for science content are simple machines, which is a review from fifth grade, reviewing things about circuits and electricity, and the gear ratios seem to be new to the kids, potential and kinetic energy, energy pathways, forces, Newton’s laws of motions, and I do them in a qualitative way.” (<i>3/29/07 interview</i>)
Used very little science knowledge explicitly	<ul style="list-style-type: none"> • Asks students how a seesaw works and probes student to have them remember the term fulcrum. (<i>1/31/07 observation</i>) • This was the only instance of science subject matter knowledge used captured in observations or interviews.

Blaine also had a strong understanding of engineering concepts and the design process (see Table 17). He had been teaching engineering principles as part of the science and technology curriculum in his school. However, he did not explicitly talk about or point out any engineering concepts or principles as he taught the LEGO-robotics engineering curriculum. He did, however, appear competent with the engineering design process as he worked with his students, which is highlighted in his pedagogical content knowledge (see next section).

Table 17. Blaine's Engineering Subject Matter Knowledge

Engineering Subject Matter Knowledge	
Knowledge Assessment	Evidence (source)
Strong understanding of engineering concepts and the design process	<ul style="list-style-type: none"> • As Massachusetts science teacher has been teaching engineering in the classroom. Taught Engineering is Elementary curriculum, a curriculum where teachers read stories about engineering and then engage students in short hands-on activities. Taught simple machines curriculum with mousetrap and solar cars. Taught windmill activity that is primarily an engineering design process activity and includes students evaluating a prototype. (12/13/06 observation) • Worked for two years in Peace Corps fixing water pumps and training others to fix water pumps. (12/13/06 observation) • Had a senior mechanical engineering student working in his classroom for a school year. (12/13/06 observation)

Blaine's Pedagogical Content Knowledge

Blaine's pedagogical content knowledge is displayed in the following tables (see Table 18, 19, 20). Blaine, as mentioned in the previous section, has taught technology and engineering in his classroom before. Blaine also knew and had previously taught the same simple machines curriculum his students learned in the fifth grade. He did a quick review of simple machines to see what they remembered (see Table 18). He was able to use this knowledge to refer back to terms like "fulcrum" when discussing design options with his students (see Table 18). This previous experience and knowledge likely contributed to his strong *knowledge of students*.

Table 18. Blaine's Knowledge of Students

Pedagogical Content Knowledge – Knowing Students (KS)	
Knowledge Assessment	Evidence (source)
Strong knowledge of students' prior knowledge	<ul style="list-style-type: none"> • "We are reviewing simple machines right now. They did it last year, and a lot of it they don't remember." (3/29/07 interview) • "They're [students] not used to going back and just running it over and over again [retesting]." (1/31/07 interview) • Asks student how a seesaw works and engages the student in a conversation to remember the term fulcrum and how one could be used in the LEGO design. (1/31/07 observation) • "A lot of them don't have the stick-to-it-ness yet [referring to complex engineering problems]." (3/29/07 interview)

Blaine’s approach to teaching the engineering unit was often directive (see Table 19). Blaine instructed his students step-by-step as he introduced them to programming. He also gave students ideas or directions to pursue and attempted to have them focus on one thing at a time. It is possible that this approach comes from his extensive teaching experience (14 years) and the fact that he is teaching sixth grade students, who may need more direction than older students.

Table 19. Blaine's Strategies for Student Understanding

Pedagogical Content Knowledge – Strategies for Student Understanding (SU)	
Knowledge Assessment	Evidence (<i>source</i>)
Uses a directed or scaffolded approach to guiding students	<ul style="list-style-type: none"> • Projected computer onto screen to show how to program step-by-step. (<i>12/13/06 observation</i>) • Working with students, suggested that they make something to hold the RCX like a chair or build something. (<i>2/6/07 observation</i>) • Student begins to have an idea... Blaine reinforces idea and extends beyond with a suggestion. (<i>2/6/07 observation</i>) • “Sometimes the kids wanted to run a course [for their programmed car] and, of course, they made it too complicated... we would simplify it down to something really basic so they could focus on one thing.” (<i>1/31/07 interview</i>) • On programming: “I would then walk them through. I would have them talk me through each step and then I would repeat it back ... making them run it 5 times and comparing it to the computer program so they could see what part of the program was faulty.” (<i>1/31/07 interview</i>) • When Blaine doesn’t have the answer: “I come up with a theory of how I might attack it ... I don’t tell them what to do, but sometimes the kids might try this idea or borrow whatever they like.” (<i>1/31/07</i>)

Blaine was not observed using any real-world examples while teaching the engineering unit (see Table 20). However, Blaine was only observed on three occasions. He did, at times, refer back to simple machine or other concepts his students had learned in previous classes (see Table 19).

Table 20. Blaine's Use of Real-world Examples

Pedagogical Content Knowledge – Real-world Examples (RWE)	
Knowledge Assessment	Evidence (<i>source</i>)
Did not use any real-world examples	<ul style="list-style-type: none"> No observations or interview responses where Blaine used real-world examples with his students.

Obstacles Blaine Faced While Teaching the Unit

Throughout teaching the unit, Blaine ran into obstacles, where he did not know what to do immediately. These obstacles were observed and recorded as outlined in the *Coding* section of this paper. The most pervasive obstacle for Blaine was working with the LEGO toolset. The following section summarizes how Blaine’s limited knowledge of the LEGO toolset became an obstacle in his teaching.

LEGO toolset.

The most salient obstacles Blaine faced in teaching the engineering unit were related to working with the LEGO toolset. Blaine admitted on several occasions that his LEGO building and programming skills needed development. Blaine rated his LEGO building skills as medium to low. The following excerpt from an interview describes his challenge:

Like last week I was trying to figure out if I wanted to build a seesaw and I wanted to put one of those axles or black pins through it and put a gear on it and run it and make the seesaw go up and down. I don't know how to get the black rod to stop spinning freely in the holes. I was messing around 15 minutes with that and didn't find an answer. Medium to low in building; I need to do some building. (*1/31/07 interview*)

The following exchange illustrates a similar description of his struggles with the ROBOLAB programming:

Researcher: What was the most difficult part for you as the teacher teaching the programming aspect of it?

Blaine: Figuring it out for myself first. And a lot of times having to do that on the fly in front of the kids without as much time, right now, to spend weekend time preparing. A lot of times I would forget something. I didn't do the light sensors over the summer so I was figuring that out and showing them basic stuff and getting it to work so they could do something more advanced. I didn't want to give them the answer but show them here is how the light sensor works. And then having them do something more complicated in inventing their own way.

Researcher: As you were figuring out things like the light sensor, was it similar to what you learned over the summer or did you relate it to other things you already knew? And how did you teach it to yourself on the fly?

Blaine: I would go back to all the tutorials they have. And mainly that was the way I did it. And a lot of times I kind of had a concept in my head of what it needed to be but for some reason I wasn't getting something. Then the kids would take whatever idea I had and run with it a little bit and get to work and I would have to go study theirs. 'How did

you program that? Oh yeah! Of course, that's wonderful!' there was a little bit of that following the kids... them leading not me leading. (1/31/07 interview)

Both these examples demonstrate Blaine was not always clear on how to use the LEGO or ROBOLAB programming to accomplish what he was trying to do. However, for both the programming and building it appeared that he did understand conceptually what he was trying to accomplish and only struggled trying to implement the ideas with the toolset. In the first example, when Blaine was assisting the student group in their pitcher-pouring device, he was observed discussing with the students the idea of using a lever and fulcrum to accomplish their task (1/31/07 observation). He was able to teach the students about this simple machine and they understood how it would apply to their project. He and his students struggled when they tried to implement this idea with the LEGO. A similar situation with a different group was also observed (2/6/07 observation). The students were creating a lift device that used a hoist setup to lift a LEGO platform. Their issue was that once the LEGO platform reached the top and stopped, the weight of the platform caused the platform to slowly move back down as the frictional load from the LEGO motors was not sufficient to keep the platform at the top. Blaine worked with the students and discussed that they needed more resistance or friction at the top after the lift stopped. However, Blaine was unsure how to implement this with the LEGO or the programming and asked the researcher how he might increase the resistance with LEGO. The researcher made some suggestions and Blaine told the students to try them out and if they were not able to finish in time (this was their last building session) they could just talk about how they would improve their device with future work. Faced with these perturbations, like Caitlin, Blaine appears to be exhibiting an alpha-behavior in his approach (Gruber & Voneche, 1977). He has his own

conceptual understanding of what should happen, but cannot, even after working at it, get beyond his lack of knowledge and resorts to asking for outside help.

Blaine's struggle with the LEGO toolset implies that teachers may need well-developed knowledge of the toolset being used in the classroom. However, this does not necessarily mean they would be unable to teach without this knowledge. Blaine was able to continue to guide his students even if he could not help them solve the problem at hand. Blaine would likely benefit from more experience with the LEGO toolset and can likely gain that experience "on the job" while teaching his students.

Blaine Summary

What subject matter knowledge did Blaine use while teaching the unit? Blaine did not use any math knowledge explicitly, did use some science knowledge, and did not use any engineering knowledge explicitly. Even though Blaine did not use much science or engineering knowledge explicitly, it did appear that he was using it implicitly as he guided his students through the design process. For example, Blaine often discussed possible solutions with his students that incorporated gears or changing the speed of the gearing. Blaine has taught engineering in the classroom before and was skilled in guiding his students through the engineering design process as is seen in his pedagogical content knowledge as well as his student's final projects, which scored well for use of simple machines (see Appendix B for student project assessments).

Blaine's pedagogical content knowledge included a strong understanding of his students. He was familiar with their prior curriculum regarding simple machines and referred back to this content with his students. This prior knowledge appeared to be present in his methodical approach to guiding and directing his students through the design projects. The most salient

obstacle in Blaine's teaching of the engineering unit was his limitations regarding the LEGO toolset. Blaine was not as comfortable with the ROBOLAB programming or LEGO building as he was with the engineering concepts. With time and experience with the toolset Blaine should be well prepared to continue teaching this type of curriculum.

Discussion

This section will compare and contrast the results from the three teachers and include some of the key findings regarding the teachers' subject matter and pedagogical content knowledge. First, the subject matter the teachers used is highlighted followed by some discussion of how this knowledge may be developed in future middle-school engineering teachers. Then, the pedagogical content knowledge the teachers used and developed will be outlined in the categories: *knowing students*; *strategies for student understanding*; and *real-world examples*.

Subject Matter Knowledge

The primary research question driving this study is what subject matter knowledge and pedagogical content knowledge do middle-school teachers use and develop teaching engineering? First, we will discuss the subject matter portion of this question. One hypothesis going into the study was that the math teachers would transfer their math knowledge and the science teacher would transfer his science knowledge to the engineering challenges. A second hypothesis was that both the math and science teachers would lack some important engineering subject matter knowledge throughout teaching the engineering unit. The question was how they would use what they already knew to compensate for what they did not know.

Subject Matter Knowledge Used

The first hypothesis was supported, but with limited evidence. The teachers did not appear to use much math or science knowledge while teaching the unit. However, on the few times that they did rely on subject matter other than engineering, the math teachers related back to math and the science teacher back to science. Caitlin, a math teacher, highlighted fraction multiplication when teaching about gears and gear ratios. She did not spend any time talking about the physics behind gears and how they create mechanical advantage. Michael, also a math teacher, talked to a student about how his car's chassis had "intersecting" or non-parallel sides and how symmetry was important in designs. Michael admitted that he struggled identifying the physics concepts at play, and how to guide his students to better designs by optimizing the physics of their designs. Blaine, on the other hand, as a science teacher, discussed the ideas of simple machines with his students and how they could implement them into their designs. For example, with one group he discussed how they could use a fulcrum and lever for their drink-pouring mechanism. For the engineering unit used in the study, simple machines and simple physics was much more prevalent. From this limited data, it appears that science knowledge—simple machines and mechanical advantage—is more prevalent than math knowledge in this particular engineering unit. Thus, the math teachers with limited knowledge of simple machines and mechanical advantage are at a disadvantage when working with their students to create their LEGO designs. For this engineering unit, the math teachers would benefit from specific development opportunities around developing this knowledge. These results highlight the importance of clear curriculum design and professional development. The engineering unit used in this study had many ties to physics concepts and not as many to mathematics concepts. If math teachers are going to teach engineering, they may have much more success with a curriculum

that highlights the mathematical connections to engineering. Having design challenges that were math-centric would be needed to explore this question further.

Subject Matter Knowledge to be Developed

The second hypothesis was that both the math and science teachers would show limited engineering or science knowledge that could hinder their teaching of the engineering unit. The study is too small to make any causal claims; however, looking at the students' projects, some conclusions may be drawn about how the teachers influenced their students. The researcher assessed each group's final project (see assessment rubric Appendix C) as a possible indicator of how well students were able to incorporate gears, sensors, sturdy design, programming through the engineering design process. For example, Caitlin's students' scored (see Appendix B) lower with regards to implementing mechanical advantage (average 1.0) into their designs than did Michael (3.0 average) and Blaine's (2.67 average) students. Did Caitlin's lack of knowledge about physics and simple machines limit her students in implementing simple machines into their designs? There are myriad other factors that could have led to this, but, as Ball and McDiarmid (1990) note, a student will usually only be able to gain as deep an understanding as their teacher. Caitlin's students actually spent more time talking formally—as groups, with worksheets, and in lecture style—about gears in their unit than did the students in Blaine and Michael's groups, yet they did not implement them as well into their designs. Before she taught the lesson on gears, Caitlin stated that she had done some research on the Internet and had made a supplemental worksheet on gears for her students. However, this did not appear to be enough for Caitlin to be comfortable teaching the topic, nor did it translate to her students using and understanding gears. To understand what knowledge could be developed in Caitlin's case, let us look at the cases of

Michael and Blaine, whose students successfully implemented mechanical advantage with simple machines in their final projects.

Michael was also limited in his physics and simple machines knowledge, as he expressed in an interview, but his students did include sophisticated simple machines in their projects. Michael's prior knowledge and experience with LEGO and building LEGO robots may explain this. Michael knew how to work with the LEGO gears and knew how to put them together to create different kinds of motion. In one instance, Michael came to a physics concept he did not understand but then was able to find the information he needed and implement it with the LEGO. For example, Michael did not know if pulleys worked the same way as gears in terms of increasing and decreasing torque and rotational speed. After asking the observer and learning that they worked just like gears in that sense, he was able to guide the student to successfully implement pulleys into the LEGO design. This evidence shows that a teacher's comfort and experience with the instructional toolset, in this case LEGO, allows them to more easily adapt concepts they do not know well. Perhaps, for this engineering unit, in addition to physics knowledge development, Caitlin would have benefited from more LEGO building experiences. Which leads us to the case of Blaine. Blaine has a strong physics and science background, as observed in the classroom and acquired from his education and experience as a science teacher. However, he is somewhat limited in his LEGO building experience, or, as he put it, his LEGO building skills are "medium-low." Even with limited LEGO knowledge, Blaine was able to guide his students to implement mechanical advantage and gears into their designs. Blaine also asked questions of the observer in the classroom; however, his questions focused on how to use the LEGO to implement the concept he or his student had in mind.

The cases of Michael and Blaine provide small pieces of evidence that there are two types of knowledge—knowledge specific to the materials used (in this case LEGO) and the content knowledge underlying the unit—that, when incorporated, lead to more sophisticated designs by the students. What is not clear in this argument is whether or not Michael and Blaine’s students understand how the simple machines work in their designs. I would argue that the students are learning what the teachers understand themselves. Again, the argument from Ball and McDiarmid (1990) is that a pupil will only gain as deep an understanding as their teacher has. For Michael’s students, they are likely coming away with more knowledge of how to build and create motion with gears, and for Blaine’s students they are coming away with some ideas of how gears or simple machines work. Both are useful and important knowledge. Given a finite time for development, Caitlin may benefit from an equal amount of work with the LEGO and engineering concepts, Michael with more time on the physics and engineering concepts, and Blaine with more time with the LEGO.

These claims may seem obvious. Of course, more physics knowledge will help the math teachers and more LEGO building experience would help any teacher teaching such a unit. However, teaching engineering at the middle-school level, it is unclear as to how much physics knowledge is necessary. The cases of these teachers begin to expose the more specific types of knowledge that are actually used in the classroom with the students. The findings also suggest that a more detailed content analysis of this and future engineering units would allow more targeted teacher professional development opportunities. These findings can also begin to formulate what the “ideal” teacher looks like. Especially for this particular unit, a teacher with a physics, engineering, computer science, or technology degree would be ideal. Having hands-on experience with technology or design, prior LEGO experience, or any such experience where the

engineering design process is central to constructing an artifact would give teachers the opportunity to have developed and applied relevant subject matter knowledge.

Pedagogical Content Knowledge Used and Developed

The other half of the primary research question for the study includes what pedagogical content knowledge is used and developed by the teachers as they teach this engineering unit. Given that pedagogical content knowledge is generally developed in practice either while teaching or in lesson planning (Shulman, 1987; Veal, Tippins, & Bell, 1998), this section will assume the pedagogical content knowledge used during the unit was also knowledge developed during the unit. However, this does not imply that these teachers were not applying their math or science pedagogical content knowledge in these situations. The discussion of the pedagogical content knowledge used and developed is broken into the categories of *knowing students*, *strategies for student understanding*, and *real-world examples*.

Knowing Students

In this category of pedagogical content knowledge—knowing the students—was teachers expressed difficulty in assessing what the students knew and were learning about engineering and the concepts covered in the unit. Engineering design challenges are unique in that students come up with many different solutions, constructed by students implementing diverse concepts. It is difficult from the final artifact, alone, to judge whether or not the students fully understand how and why their design does or does not work. Beyond the concepts the students are implementing in their designs, the teachers are assessing their student's understanding of the engineering design process.

The teachers in the study were teaching after-school programs where formal assessments were not required, which is likely one reason for the difficulty in assessing what their students were learning. Both Michael and Caitlin expressed that they did not believe that their students came away understanding how gears work even though some of their students did successfully implement gears into their projects. Throughout the unit, Michael expressed that he was not sure exactly what his students were learning. However, Michael and both Caitlin and Blaine expressed in the final interviews, after the unit was completed, that they believed their students came away with a strong understanding of the engineering design process. They, specifically, felt the students came away with knowledge and skills represented by the test and evaluate, communicate solutions, and redesign steps of the engineering design process as seen in steps 6-8 in Figure 1. This is a good sign considering that one of the learning objectives of the engineering unit is for students to understand the engineering design process. My hypothesis is that a teacher can better assess students' understanding of the engineering design process than their understanding of the engineering and other concepts being applied given that the unit was taught in an afterschool program with no formal assessment. This is based on the fact that the students are actively and physically engaged in the engineering design process during the lessons. A teacher can see when a student tests their device, communicates their solutions and problems, and then redesigns their device. They cannot necessarily see whether a student understands that by using the specific set of gears they are doubling the torque of the wheelchair's axles. More formal assessments would need to be used to capture the students' gains in conceptual knowledge.

Strategies for Student Understanding

The data revealed many strategies the teachers used to teach and guide their students. Looking at these strategies as a whole, the teachers were acting similar to a coach. Blaine actually described his role in the engineering classroom more as a coach, which was different from how he would describe his teaching in the science classroom (3/29/07 interview). As a coach, the teachers would give some instruction or guidance, and then circulate around the room looking to assist or guide students on a case-by-case basis. Something to note here, is that when the teachers were more comfortable with the topic, they were more likely to take an inquiry-based approach with their students. When the teachers were less comfortable with the topic, they resorted to a more directed, instructional approach or called upon the researcher to assist.

Real-world Examples

Using real-world examples to relate the content to students' lives involves a number of types of knowledge. Teachers have to *know their students* and the subject matter knowledge. Choosing real-world examples such as video games (Michael) or cell phone features (Caitlin) involves knowing that these examples relate to the students' lives and that the engineering, science, or math concept is used similarly in each case. Using real-world examples is also a *strategy for student understanding* and can be an effective method in presenting a concept to a student. These real-world examples could be accumulated and shared over time and provided in teacher development materials for such engineering units.

Conclusion and Implications

The purpose of this study was to explore how middle-school math and science teachers face the challenge of teaching engineering and what knowledge they use. The purpose was

intentionally exploratory in nature because there is little prior research in the content area of engineering to provide guidance. The study did provide results and findings that will help design future studies, and also had some shortcomings that need to be addressed for future research. One success of this study is that it provides clear examples of both subject matter and pedagogical content knowledge that middle math and science school teachers use while teaching engineering. The study also highlights the differences in individual teacher's knowledge bases and how teacher resources and professional development can be customized for these differences. These successes also demonstrate that the observations and interviews, as conducted in the study, can be effective at identifying and understanding the knowledge teachers use in the classroom, especially pedagogical content knowledge.

The study did have a number of shortcomings that were highlighted throughout the data collection and analysis phases. One major shortcoming of the study was the difficulty in fully understanding the subject matter knowledge the teachers were using and the implications of the teachers' prior subject matter knowledge. Subject matter knowledge may be used by the teacher, but not observed because they may not explicitly say or do anything that demonstrates this knowledge. Another shortcoming was that engineering unit itself was not analyzed *a priori* in such a way that all the underlying math, science, and engineering concepts were clearly outlined such that the researcher could actively look for the use or lack of use of these concepts. The small sample size is yet another shortcoming of this study. In future studies, these shortcomings will need to be addressed.

The implications of this research study include providing insights into developing curriculum, resources, and teacher professional development, as well as methods and findings to expand research into the topic of teaching middle-school engineering. The results from this study

demonstrate that math and science teachers are able to transition into teaching an engineering unit focusing on the engineering design process with varying degrees of success. The teachers in this study had varying levels of math, science, and engineering knowledge that they each used in different ways. One key point to consider for engineering curriculum development is to make sure the connections to math and science concepts in the curriculum are clearly defined and made explicit to the teacher. This is based on the finding that the teachers in this study rarely made connections to math or science even though it was the subject they were certified to teach. The findings may also inform future teacher educators that customizing the development opportunities for individual teachers on the body or bodies of knowledge (i.e., physics, engineering, LEGO robotics) that they struggle with the most may lead to quicker and more effective implementation. The examples of pedagogical content knowledge the teachers used and developed can help curriculum developers create more robust resources for teachers to include real-world examples to link the concepts to students' lives, strategies for student understanding, and knowledge of students' understanding of engineering. The methods used in the study may be able to guide future researchers who wish to capture teachers' pedagogical content knowledge and subject matter knowledge use and development as it specifically relates to engineering.

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LESSON 1: FORM COMPANIES/SELECT A SOLUTION

OBJECTIVE

To introduce the students participating in this after school program to the theme. To have the students form their companies (teams) and to participate in their first challenge as a team. The first challenge will introduce the students to thinking critically and at the end of the lesson the students will link their strategies to the engineering design process.

BACKGROUND FOR THE TEACHER

The engineering design process is a framework used in nearly all engineering problems and solutions. The engineering design process is used in the development of new products, new processes, new systems, or in the optimization or improvement of existing products, processes and systems. While it may sound like a very technical process, the engineering design process is a common-sense approach to solving a problem. It is a process that in some form or another we have probably all used.

The Massachusetts Science and Technology Frameworks describe the engineering design process as the 8-step process below:

Step 1—Identify the Need or Problem

Step 2—Research the Need or Problem

Step 3—Develop Possible Solution(s)

Step 4—Select the Best Possible Solution(s)

Step 5—Construct a Prototype

Step 6—Test and Evaluate the Solution(s)

Step 7—Communicate the Solution(s)

Step 8—Redesign

NOTE: Included in students and teachers materials will be a fully detailed version of the Engineering Design Process.

The steps of the Engineering Design Process helps engineers produce functional, safe, reliable, competitive, usable, manufacturable, and marketable solutions.

STANDARDS ADDRESSED

2.1 Identify and explain the steps of the engineering design process, i.e., identify the need or problem, research the problem, develop possible solutions, select the best possible solution(s), construct a prototype, test and evaluate, communicate the solution(s), and redesign.

- 2.2 Demonstrate methods of representing solutions to a design problem, e.g., sketches, orthographic projections, multiview drawings.
- 2.3 Describe and explain the purpose of a given prototype.

MATERIALS

Lesson 1 All-terrain Wheelchair Prototypes Handout: need 1 copy per group
Engineering Design Process Handout: need 1 copy per student
Lesson 1 Wheelchair Specifications: make multiple copies and cut into strips
Interoffice envelope or Engineering Design Notebook: need 1 per company

SETUP

Before the lesson photocopy and distribute the drawings and handouts listed under “materials” into each group’s interoffice envelope.

GUIDING THE ACTIVITY

DISCUSS THE PROJECT

There are students your age who use a wheelchair. Imagine what gym class would be like if you were in a wheelchair. Imagine how you would approach everyday tasks such as getting books in and out of your lockers, getting lunch in the cafeteria, or seeing things on high countertops if you were in a wheelchair.

Does anyone know anyone in a wheelchair?

What are some things that are harder for them to do than they are for you?

What is something you wish you could make easier for them?

Is there anywhere they want to go that is impossible for them because of lack of access for wheelchairs?

Look for students responses to include: reach high things (locker), go to the beach, go up stairs, go in the water, go through rough terrain, play sports, etc

We have brought you together to design and develop devices and tools these students could use to improve their school experience. You have been chosen because you are students and you know best what people your age like to do. Your job throughout this project will be to develop a concept for an assistive device that will aid a fellow student who is in a wheelchair or has some other physical limitation. You will then build and program a prototype of your device. Finally, you will present your concept and prototype to a panel of judges.

Does anyone know what a prototype is?

Why would a company create a prototype?

Throughout the project we will be holding corporate trainings where you will learn how to take an idea and turn it into a design, use the LEGO robotics kits to create a working prototype, and how to effectively present your designs to the outside world. Throughout the project you will be working with a partner and you will be operating as your own corporation. Some weeks you will work as engineers, others as marketing managers, quality control testers, or salespeople as you develop and then present your prototypes.

FORM THE TEAMS

First, you must form your corporations. Your corporation will design, test and produce assistive devices for people with physical disabilities. (Teacher may assign groups or have them form their teams independently)

In the next ten minutes you should come up with a company name and your company logo. Your name and logo should help someone understand what your company does and who your audience is. You have ten minutes to finish your company name and logo. (Have the groups use MS Paint or other similar software to create their logo. Each group should also create a folder on the computer to save their future documents)

ALL-TERRAIN WHEELCHAIR CHALLENGE

Ok, it is time for your company to take on its first challenge. You all have a million-dollar decision to make today. In my hands are drawings of four proposed design solutions from four leading engineering design firms. They are looking to sell their design solutions to us so we can provide all-terrain wheelchairs to our customers. Your Company wants to buy the best solution so you can manufacture and sell it. It would mean big fat bonuses for everyone at your Company if you pick the best solution.

You all are going to work within your Companies and you'll have to decide which is the best solution ... remember millions of dollars are on the line and you'll each get a big bonus if you pick the best one!

RULES OF THE CHALLENGE

Each design has some pictures and some information about the all-terrain wheelchair. However, this information is not enough to make a decision regarding which design is the best solution. With your group you can come up with 3 questions to ask me about the designs. You will have five minutes to discuss with you group which questions to ask me. You must pick one design based on your analysis of the drawing and the responses to the 3 questions. Then after 10 minutes you will present to the entire group which solution you chose and why.

OPEN DISCUSSION OF POSSIBLE QUESTIONS (BRAINSTORM)

First, what are some questions you might want to ask about the possible solutions?

(Have students shout out many possible questions – a minimum of 5)

(Also, refer the students to the EDP handout and tell them we are now at Step 7 so they can ask questions about Steps 1-6)

Now, break into your Corporations and brainstorm a list of questions you want to ask me about the designs. Select your three best questions to ask. (Tell them they will have 5 minutes to make their final decisions)

Hand out interoffice envelope to each group

A representative from each team will approach with their 3 questions. Give the student the 3 corresponding strips from the Lesson 1 Wheelchair Specifications printout.

After you have received the additional information from me, you have 5 minutes to pick which of the 4 designs is the best. Then a representative from your company will tell the other companies which design you picked and why.

TEAMS NOW PRESENT THEIR DECISIONS

Time is up! Everyone should have a final decision and each group will now tell the class why you picked that solution.

Have the team stand up and present their decision and have them explain their choice

Possible questions to ask after or during the presentations:

Why did you select the 3 questions you did?

Would anyone want to change the design they selected based on another groups presentation?

Why?

DISCUSSION

Pass out the Engineering Design Process Handout (1 per student)

This handout shows the Engineering Design Process. When engineers create a product they will follow a process like this. The companies that submitted the wheelchair designs to you went through this process and made it up to Step 7 “Communicate the Solutions”, which is in the form of the drawings they submitted to you.

So, these companies identified a need (direct the students’ attention to Step 1 on the worksheet). The need was that people in wheelchairs wanted to be able to go hiking, go to the beach, or travel through the snow.

Then the company would have done some research into this need or problem as you see in Step 2 (*direct the students’ attention to Step 2 on the worksheet*). What types of research do you think they did?

Take a few answers from the students

Next, after they have done a lot of research they would have brainstormed all the possible solutions or all the possible wheelchair designs they could make (*direct the students’*

attention to Step 3 on the worksheet). Why do you think it would be important to think of more than one possible solution?

Take student answers

Then in Step 4 (*direct the students' attention to Step 4 on the worksheet*) they would pick what they think will be the best solution. What might be some criteria for selecting the best solution? *Take student answers*

Who can tell me what they did in Step 5 (*direct the students' attention to Step 5 on the worksheet*)? You may ask again: What is a prototype? Why would you want to build a prototype?

From the information you received today what types of testing do you think they did on the wheelchairs (*directing the students' attention to Step 6 on the worksheet*)

How did they communicate the solution to us, which is Step 7?

Why do you think you would want to follow this process to make your product?

Take 2-5 answers

This is a very important process for making a product. You will be using the Engineering Design Process to make your final assistive device product. Keep this in a safe place because we will be following this process and looking back at it often.

END

APPENDIX B

Student Final Projects

The researcher using an assessment rubric (see Appendix C) assessed the final projects based on use of mechanical advantage, sturdiness, programming, use of sensors, and innovation. Each category was rated on a 0-4 scale.

Michael's Students' Final Projects

Project	Description	Total	Mechanical Advantage	Sturdy	Programming	Sensors	Innovation
Automatic shower	Assists persons with washing themselves in the shower. An enclosure with a motorized door that opens and closes at the press of a button.	11	2	3	2	2	2
Automatic toilet	Automated personal hygiene device built into a toilet to assist with cleaning. The mechanism is built into a model toilet and moves in and out and also spins in the center of the toilet.	14	4	2	2	2	4
Soccer wheelchair	Wheelchair that helps someone play soccer. Very innovative design that contorted the wheelchair to kick and receive a ball.	14	4	4	1	1	4
Automatic closet	A closet with a motorized rotating hook to find clothes with limited arm movement. Note: The project was not fully finished.	9	2	3	0	2	2

Caitlin's Students' Final Projects

Project	Description	Total	Mechanical Advantage	Sturdy	Programming	Sensors	Innovation
Singing wheelchair	Wheelchair that moves forward and plays a song when you press a button.	9	0	3	2	2	2
Automated wheelchair	Two motor basic car with two touch sensors that allow the user to have the car go forward or turn to the right.	12	0	3	4	3	2
TV arm wheelchair	Wheelchair with arm that raises and lowers a TV using simple gear setup.	9	2	3	2	0	2
Wheelchair with arm	Wheelchair with arm that raises and lowers objects using simple gear setup.	11	2	3	2	0	2

Blaine's Students' Final Projects

Project	Description	Total	Mechanical Advantage	Sturdy	Programming	Sensors	Innovation
Food Chopper	Device that chops food. Chopping mechanism that holds knife and conveyor belt to move food. Uses rack & pinion gears, cam, worm gear.	17	4	3	3	3	4
Wheelchair Hoist	Two motor basic car with two touch sensors that allow the user to have the car go forward or turn to the right.	12	2	3	2	2	3
Drink Pourer	Device that tips a water pitcher to assist someone in pouring. Note: Group did not finish their design.	8	2	2	0	1	3

Average Final Project Scores

Name	Total	Mechanical Advantage	Sturdiness	Programming	Sensors	Innovation
Michael	12	3	3	1.25	1.75	3
Caitlin	10.3	1	3	2.5	1.75	2
Blaine	12.3	2.67	2.67	1.67	2	3.33

APPENDIX C

Assistive Robot Design Challenge Assessment Rubric

Score	Mechanical Advantage	Sturdy	Programming	Sensors	Innovation
0 N/A					
1	Attempted to use gears or another simple machine, but did not implement correctly.	Does not reliably stay put together. Never works without some hands-on “help”	Very basic program that simply runs motors for a certain amount of time. Either a built-in program or a very simple program (motor on, time, motor stop)	Has a sensor but does not actually work or serve a proper function.	Is a basic car/wheelchair and has no additional programmed features beyond moving forward and backward.
2	Successfully used gears or other simple machine in a simplistic manner. (e.g. motor connected to one gear to turn tires)	Does not reliably stay put together but does work at times without hands-on “help”	Basic program that controls motor operation and may have sensor control or other additional control features.	Successfully uses one sensor properly.	Is a basic car/wheelchair with a simple add-on feature OR very simplistic already existing other design.
3	Successfully used multiple gears or simple machines OR used gears or simple machines in an advanced manner that truly exploited the mechanical advantage or transfer of motion properties	Reliably stays put together and needs to be adjusted or “tweaked” every once in a while	Program that uses loops or task splits or any other advanced programming function beyond the straight linear options.	Successfully uses more than one sensor OR uses one sensor in a “non-traditional” manner (e.g. uses touch sensor for something other than an on/off button the user presses)	Complex add-on feature to a basic car/wheelchair OR complex idea that may have been done before but is being done in a new/different way.
4	Successfully used multiple gears or simple machines in an advanced manner that truly exploited the mechanical advantage or transfer of motion properties	Reliably stays together and can be run multiple times without needing adjustment or tweaking.	Advanced program with multiple sensors, loops or other structural features.	Successfully uses multiple sensors in “non-traditional” manners.	Completely original idea with sophisticated design ideas.