AC 2010-447: MIDDLE-SCHOOL TEACHERS' USE AND DEVELOPMENT OF ENGINEERING SUBJECT MATTER KNOWLEDGE

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Middle-School Teachers' Use And Development Of Engineering Subject Matter Knowledge: Analysis of Three Cases

Abstract

This paper reports on a portion of a study of three middle school teachers (two mathematics teachers and one science teacher) as they taught a unit of engineering instruction. The study investigated the subject matter and pedagogical content knowledge these teachers used and developed as they taught with materials that used LEGO to introduce students to the engineering design process while designing and building a computer-controlled assistive device that utilizes motors and sensors. This paper focuses and reports on the subject matter knowledge the teachers learned and used, including a subject new to them—engineering, based on teacher interviews and classroom observations. The data revealed how a teacher's knowledge of physics or engineering impacted their teaching, and that the teachers rarely connected their mathematics or science knowledge to make connections to engineering explicitly. One conjecture made from the data collected during 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., concepts in physics, mathematics, programming and engineering design).

Introduction

The purpose of this study was to explore the knowledge middle-school mathematics and science teachers use and develop as they teach engineering in an afterschool program. The study specifically investigated what mathematics, science, and engineering subject matter knowledge and pedagogical content knowledge they used and developed. This paper reports on results relating to the teachers' use of mathematics, science, and engineering subject matter knowledge and not on their development of pedagogical content knowledge. Similar studies have been conducted that have looked at mathematics and science teaching; however, little research has been done regarding what educators learn and do when teaching engineering in middle schools. The study reported in this paper investigated three in-service, middle-school teachers with little engineering background, explored the knowledge they used and developed to teach an engineering curriculum, and asked the following research question:

> What mathematics, science, and engineering *subject matter knowledge* do middle-school mathematics and science teachers draw upon and incorporate as they teach an engineering instructional unit on robotics?

Engineering in the Middle School Classroom

Engineering education in the United States (US) K-12 setting is an idea that has been gaining attention as professional and educational groups push for its inclusion into the pre-college STEM classrooms [1-4]. Other countries such as the United Kingdom (UK), Australia, New Zealand, and Canada include design and technology in their pre-college curriculum [5-8].

The International Technology Education Association (ITEA) places engineering design within technology education classrooms and describes 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" [1]. The National Research Council (NRC)[3] recognizes the importance of the relationship between the processes of scientific inquiry and "technological design", where the latter involves identifying problems, implementing and evaluating solutions, and communicating about them to others. Both the NRC and ITEA describe engineering design as including a process for designing the use of knowledge and skills from various domains (i.e., mathematics and science) and create solutions to problems.

Engineering, technology, and design are terms interspersed throughout the various curricular standards and guidelines highlighted above. Many times, these terms are used synonymously. For this paper, "engineering" is used to describe the subject matter focused on in this study. The aforementioned curricular standards each define and highlight different parts of engineering, technology, and design slightly differently. However, they follow a similar model whereby some knowledge (e.g., mathematics, science, engineering, and technology) is applied through some process (e.g., the engineering design process) to create some technological product or end. The design process—that is, the application portion of the definition—involves weighing the benefits, costs, and constraints of design options that arise from these domains of knowledge. The specific technological end (i.e., bridge design or robotics) serve as the context for the engineering design problems posed to students. For the study reported in this paper, teachers used robotics as the context to teach the engineering design process and basic engineering principles (e.g., gears, computer programming, construction, and electronics). Robotics involves the application, study, and design of using computer-controlled devices (robots) to perform tasks for human endeavors and is an interdisciplinary engineering field that draws upon mechanical engineering, electrical and electronic engineering, computer science, biology, human factors, and other disciplines [9]. With open-ended robotics challenges, teachers and students can explore and apply mathematics, science, and engineering concepts to real-world problems. The specific curriculum used for the study reported in this paper, which takes advantage of the LEGO robotics toolset, will be detailed later in the *Methodology* section.

The study reported on in this paper investigated in-service middle-school mathematics and science teachers as they implemented in an afterschool setting a unit of instruction that focused on robotics and the engineering design process, and attempts to complement the work of Moreland and Jones[10-12]. Moreland and Jones' work investigated technology teachers' concepts of technology, knowledge of technology, and knowledge of teaching. The current study aims to reveal similar findings for teaching engineering.

Subject Matter Knowledge for Teaching

Teaching engineering can entail making connections to mathematics and science subject matter knowledge as well as engineering knowledge. It was expected that middle-school engineering teachers would be observed applying mathematics, science, and engineering knowledge to help students address the robotics problems presented in the curriculum. Since literature on subject matter knowledge for teaching in the area of engineering is scarce, the paper highlights prior research in mathematics, science and technology education. The assumption being that because engineering employs mathematics, science and technology, issues in teaching these may be similar to teaching engineering.

A teacher's subject matter knowledge in the subject they teach is clearly important. In mathematics, teachers with limited depth of knowledge of the subject matter they teach fail to promote deep conceptual understanding in their students. Ma[13] found US elementary mathematics teachers did not have as deep an understanding of the basic arithmetical operations as compared to Chinese teachers, and were prone to teaching these operations as rules to be followed. Ball[14] revealed a similar lack of depth in understanding among prospective US teachers, and emphasized that the prior coursework of the teachers did not predict strong understanding of the subject. Similarly, the Third International Mathematics and Science Study (TIMSS) of eighth-grade science teaching in 19 countries found that 66% of science (biology, chemistry, and earth science) lessons in these classrooms were devoted to acquiring facts, definitions, and algorithms as opposed to making connections among ideas, patterns, and explanations[15]. Exacerbating this issue are the findings by Hill, Rowan, and Ball[16] that showed a teachers' mathematical knowledge was positively related to students' achievement. The measure the team created to assess content knowledge teachers would use in the classroom proved to be a better predictor of students' test scores than teachers' college coursework, certification, and years of experience. Studies in science education have shown that teachers with strong subject matter knowledge are better able to lead their classrooms in inquiry exercises focusing on concept acquisition and problem solving[17-19].

In technology, Jones and Moreland found that the teacher's knowledge of technology directly impacted their students' learning[11]. Teachers with a poor concept of technology and unable to relate the nature of technology (i.e., the how and why of technology) to the subject matter of technology left their students with poor understandings of this connection. Instead, students were left with a simplistic concept that technology is merely making things. After teacher professional development, these same teachers were able to impact their students' understanding to include a broader and more accurate representation of the nature of technology. New middle school engineering teachers without formal engineering courses or experiences may have limited conceptions of engineering and engineering design possibly leaving students with simplistic views of engineering and engineering design. These teachers may also rely on what Lampert[20] described as intuitive knowledge developed through a lifetime of living in an engineered world.

These findings highlight the importance of understanding the depth of a teacher's subject matter knowledge beyond just considering what college courses they may have taken. The depth of a teacher's engineering knowledge may, currently, be difficult to assess, but is something that needs to be considered going forward. This will include understanding the role of mathematics, science, and technology knowledge in teaching engineering.

Methods

Study Design

The present study followed three middle-school teachers as they taught a LEGO-robotics engineering curriculum for the first time. The teachers each participated in the same two-week summer professional development workshop developed and led by the first author of this paper. The teachers were interviewed and their classes were observed over the course of the study. It is important to note the teachers each taught the curriculum in an afterschool setting. One cannot directly relate findings from an afterschool program to those of in-classroom settings, which is problematic for this study. However, this research study focused on teacher knowledge and the afterschool setting still required the teacher to present new ideas to students and then work with them as they designed their final projects. Thus, researching the teacher's subject matter knowledge was still possible.

The Curriculum

The engineering curriculum developed by the first author of this paper and colleagues at Northeastern University and TechBoston (part of the Boston Public Schools) 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 curriculum consisted of 11 lessons that took approximately 15 hours to teach (each lesson was approximately 1.5 hours long). 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.

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 first author. The teachers were selected from the group of 25 teachers that participated in the aforementioned summer professional development workshop. Teachers from schools in the Boston area were recruited to participate in the summer workshop. The study participants were selected due to the proximity of their schools to the first author and the timing of their afterschool sessions. A brief description of the teachers follows. All names used are pseudonyms.

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

Michael, an eighth-grade mathematics teacher, was in his second year teaching in an urban public school system. Michael earned his Bachelor's degree in computer science, and his Master's degree in mathematics education. Michael started an afterschool robotics club with materials that had been left behind by a retired teacher while he was working as a substitute 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. 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.

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

Caitlin, a sixth-grade mathematics teacher, was in her second year of teaching within an urban public school system. She received a Bachelor's degree in mathematics and received her Master's degree in teaching. 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 over five 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 mathematics, 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 a product. She also explained that many of the mathematics and science courses she took were often linked to engineering or engineering problems. Caitlin was not very familiar with the LEGO robotics toolset.

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

Blaine, a middle-school science teacher, was in his 14th year of teaching. Blaine taught elementary science for four years and had been teaching middle-school science for the past ten years. He received his Bachelor's degree in International Relations, but did considerable science coursework before switching majors from wildlife biology. After graduating from college, Blaine joined the Peace Corps where he fixed and maintained water sanitation pumps and later trained others to do this, something he described in an interview as highly related to engineering. He later received a Master's degree in teaching and began teaching science. In an interview, 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 robotics building and programming.

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 this study. These two methods of data collection allowed for the teachers to both verbalize what they were doing and experiencing, and allowed us 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.

Data analysis

The research question addressed in this paper consists primarily of the construct of subject matter knowledge. The review of the literature of subject matter knowledge served as a foundation to conduct a domain analysis as described by Spradley [21], where subject matter knowledge could be broken down into more detailed types of knowledge. From the research question, it was clear that each instance of a teacher displaying knowledge of mathematics, 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.
- MSK – Mathematics subject matter knowledge.
- ESK – Engineering subject matter knowledge.

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[22, 23], 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[22] process of equilibration where the teachers assimilate and accommodate new knowledge.

Date	Obstacle	Strategy to overcome	Outcome	STEM 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. Student sees the difference.	Success. Teacher and student both understand the issue and how to resolve it.	Friction, symmetry

Figure 1. Sample Obstacle Coding.

Results

The results presented in this paper are organized by presenting the subject matter knowledge each teacher used and the obstacles they faced. 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 with additional data from each teacher's students' project assessments.

Michael (2nd year, 8th grade mathematics 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. Michael followed the curriculum quite closely, although, he chose to skip Lesson 1 because he did not 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. Hynes conducted eight classroom observations capturing structured lessons 3 and 5 and 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 afterschool sessions due to other commitments.

Michael's Subject Matter Knowledge

Given Michael's position as a mathematics teacher and his educational background, it was assumed that he came in with strong middle-school mathematics knowledge. However, he did not appear to rely upon or use his mathematics knowledge very often while teaching the unit. Table 1 includes Michael's single use of explicit mathematics knowledge that was captured during the classroom observations and interviews. It should be noted that the observations and interviews likely did not capture all the knowledge Michael used while he was teaching and he was likely using much more subject matter knowledge while he was teaching.

Table 1. Michael's Mathematics Subject Matter Knowledge.

Mathematics Subject Matter Knowledge	
Knowledge Assessment	**Evidence *(source)***
Strong middle-school mathematics knowledge.	• Certified middle-school mathematics teacher. • Teaches eighth grade algebra *(11/20/06 interview).* • Master's degree in mathematics education *(11/20/06 interview).*
Used very little mathematics knowledge while teaching the curriculum.	• Only 1 instance of using mathematics SMK in class below: • Helped student identify why the wheels on the geared wheelchair wouldn't spin *(11/16/06 observation).* 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" *(11/20/06 interview).*

The observations also revealed that Michael used little science knowledge while 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 2). 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 2. Considering that Michael's background is in mathematics and computer science, it is not a surprise that he may lack some of the basic physics knowledge that is necessary in analyzing robotics devices. How much physics knowledge Michael would need to teach engineering in the future is unclear, but as he admits, this is knowledge that could help him highlight concepts at play in the students' designs.

Table 2. Michael's Science Subject Matter Knowledge.

Science Subject Matter Knowledge	
Knowledge Assessment	**Evidence *(source)***
Middle-school science/physics knowledge self-described as a weakness.	• "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 interview*).
Used no accurate science knowledge explicitly.	• Used term tension instead of friction when talking about a car's wheels providing resistance for turning (*3/7/07 observation*). • No other observed uses of specific science concepts.

While teaching the engineering curriculum, Michael did use engineering subject matter knowledge. He displayed strong troubleshooting and analyses skills while working with students and their designs. Table 3 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 [24]. 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 3. Michael's Engineering Subject Matter Knowledge.

Engineering Subject Matter Knowledge	
Knowledge Assessment	**Evidence *(source)***
Strong troubleshooting and analysis knowledge with engineering design process.	• 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.	• *Computer programming* o Computer science Bachelor's degree (*11/20/06 interview*). o Demonstrates knowledge of DO and WHILE loops and FORKS (*11/20/06 interview*). • *Gears/Pulleys* o 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*). o Asks Hynes how pulleys work (whether they work like gear ratios). Hynes says yes and Michael continues to work with student to implement pulleys (*3/7/07 observation*).

Obstacle 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 [25]. When Michael encountered such an obstacle, his approach, knowledge used, and outcome were observed and recorded, as outlined earlier. The following section reveals how Michael deals with one such obstacle and the knowledge he calls upon to overcome it. This obstacle was the most salient example captured in Michael's teaching. We report here on his uses of subject matter knowledge to address the obstacles he faces.

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 Michael describes 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.
>
> *Hynes*: 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.
>
> *Hynes*: 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"[23]. This was a behavior he displayed on multiple occasions throughout teaching the unit. Michael's approach also exemplifies Piaget's equilibration process[23]. 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 at stake 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 was resolved (and he could reach a new level of equilibration). Jonassen and Hung [26] 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 background, which could contribute to his engineering subject matter knowledge, 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. Is there some way to connect this specifically to SMK?

Michael also demonstrated his LEGO building/engineering and mathematics subject matter 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 was referring to prior LEGO building knowledge. His mathematics subject matter knowledge was displayed when he explained that the issue he saw was that the "beams weren't parallel to each other, they were becoming intersecting."

Caitlin (2nd year, 6th grade mathematics 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 added content on gears in the third lesson. All Caitlin's student groups completed their final projects. Caitlin chose, in one session, to redo a lesson some students had missed 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 *The governor rules machine*[i], using crown and bevel gears. The significance of this decision will become apparent later. Hynes 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 mathematics subject matter knowledge based on her being a certified middle-school mathematics 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 mathematics knowledge explicitly during the engineering unit. She did use mathematics to help explain gears and gear ratios, but that was the only instance in which she was observed explicitly using mathematics (see Table 4). While Caitlin used mathematics 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 5).

Table 4. Caitlin's Mathematics Subject Matter Knowledge.

Mathematics Subject Matter Knowledge	
Knowledge Assessment	**Evidence *(source)***
Well-developed (education & experience) middle-school mathematics knowledge.	• Certified middle-school mathematics teacher. • Teaches sixth grade mathematics *(4/6/07 interview).* • Bachelor's and Master's degrees in teaching *(11/17/06 interview).*
Used very little mathematics knowledge while teaching the curriculum.	• "When I was working with my students, I was trying to apply mathematics to them [gears]… like what fraction is a whole turn" (*11/17/06 interview*). • This was the only instance of mathematics subject matter knowledge used in observations or interviews.

Table 5. Caitlin's Science Subject Matter Knowledge.

Science Subject Matter Knowledge	
Knowledge Assessment	**Evidence *(source)***
Unclear what students are learning in middle-school science/physics.	• 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.	• 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 6). 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 6. Caitlin's Engineering Subject Matter Knowledge.

Engineering Subject Matter Knowledge	
Knowledge Assessment	**Evidence *(source)***
Demonstrated knowledge of the engineering design process.	• Works with student to analyze their design and asks questions about the necessity of different features and then suggests a redesign (*11/9/06 observation).* • Engages students in inquiry about what a prototype is and its purpose (*11/30/06 observation*). • Went to a mathematics, science, and engineering high school and took a course where they went through the engineering design process and created a prototype (*11/17/06 interview*).
Demonstrated basic knowledge of engineering concepts.	• Basic understanding of gears. Knew how to find gear ratios, knew changed speed and energy/work, used driver/follower terminology correctly (*11/9/06 observation*). Seemed unsure of her knowledge of gears, looked at Hynes after she realized she was probably wrong with term "gearing up" (*11/9/06 observation*). • 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 (*2/8/07 interview*). • Did not know what kind of engineering knowledge would be useful to learn… just thought she "probably" needed more (*2/8/07 interview)* . • 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 (*11/30/06 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 Hynes 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:

> *Hynes*: How comfortable are you with your knowledge of gears?
>
> *Caitlin*: Umm… (laughs). My knowledge of gears is what I presented to them… yeah.
>
> *Hynes*: 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.

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

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 Hynes 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 Hynes and asked how he would approach this. Hynes 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 mathematics 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 mathematics 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. 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 Hynes 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 [23]. 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 (mathematics) to the change of speed and torque. When knowledge beyond this was required, she was unable to move beyond it, and, on one occasion, deferred to Hynes.

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 addressed 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 mathematics major could not teach engineering or gears, but that additional development or experience may aid them in teaching such a curriculum.

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 retired engineer 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. Hynes had scheduling conflicts that resulted in just three classroom observations in Blaine's class (Lesson 5, and two final project 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 8). 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. We were unable to assess his mathematics knowledge because he did not explicitly use mathematics knowledge while teaching nor did he mention it in interviews (see Table 7).

Table 7. Blaine's Mathematics Subject Matter Knowledge.

Mathematics Subject Matter Knowledge	
Knowledge Assessment	**Evidence *(source)***
Unable to assess mathematics knowledge.	• No evidence for assessing mathematics subject matter knowledge.
Used no mathematics knowledge while teaching the curriculum.	• No instances of mathematics knowledge used explicitly captured in the interviews or observations.

Table 8. Blaine's Science Subject Matter Knowledge.

Science Subject Matter Knowledge	
Knowledge Assessment	**Evidence *(source)***
Strong middle-school science knowledge.	• Certified science teacher (*12/13/06 observation*). • 14 years teaching science (10 middle-school, 4 elementary) (*12/13/06 observation*). • "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" (*3/29/07 interview*).
Used very little science knowledge explicitly.	• Asks students how a seesaw works and probes students to have them remember the term fulcrum (*1/31/07 observation*). • This was the only instance of science subject matter knowledge use captured in observations or interviews.

Blaine also had a strong understanding of engineering concepts and the design process (see Table 9). 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, which we will report on in another paper.

Table 9. Blaine's Engineering Subject Matter Knowledge.

Engineering Subject Matter Knowledge	
Knowledge Assessment	**Evidence *(source)***
Strong understanding of engineering concepts and the design process.	• 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*).

Obstacles Blaine Faced While Teaching the Unit

Throughout teaching the unit, Blaine ran into obstacles, where he did not know what to do immediately. The following section summarizes how Blaine's limited knowledge of the LEGO toolset—the most pervasive obstacle for Blaine—became an obstacle in his teaching.

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:

> *Hynes*: 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.
>
> *Hynes*: 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 about how to implement this with the LEGO or the programming and asked Hynes how he might increase the resistance with LEGO. Hynes 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[23]. He has his own conceptual understanding of what should happen, but cannot, even after working at it, move beyond his lack of knowledge and he thus resorts to asking for outside help.

Blaine's struggle with the LEGO toolset might imply that teachers may need a 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 could likely gain that experience "on the job" while teaching his students.

Discussion

One hypothesis going into the study was that the mathematics teachers would connect their mathematics knowledge and the science teacher would connect his science knowledge to the engineering challenges. A second hypothesis was that both the mathematics and science teachers would lack some important engineering subject matter knowledge. 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 mathematics or science knowledge while teaching the unit. However, on the few times that they did rely on subject matter other than engineering, the mathematics teachers related back to mathematics and the science teacher back to science. Caitlin, a mathematics 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 mathematics 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 in 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 mathematics knowledge in this particular engineering unit. Thus, the mathematics 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 mathematics 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 mathematics 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 centered on mathematics would be needed to explore this question further.

Subject Matter Knowledge to be Developed

The second hypothesis was that both the mathematics 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. Hynes assessed each group's final project as a possible indicator of how well students were able to incorporate gears, sensors, sturdy design, and programming through the engineering design process. For example, Caitlin's students' scored 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 result, but, as Ball and McDiarmid [27] 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—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 is whether or not Michael and Blaine's students understand how the simple machines work in their designs. We would argue that the students are learning what the teachers understand themselves. Again, the argument from Ball and McDiarmid [27] 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 about 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 mathematics 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 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.

Conclusion and Implications

The purpose of this study was to explore how middle-school mathematics 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 provided results and findings that will help design future studies. One success of this study is that it provided clear examples of subject matter knowledge that middle school mathematics and science teachers use while teaching engineering. The study also highlighted 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.

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. 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 mathematics and science teachers are able to transition into teaching an engineering unit focused on the engineering design process with varying degrees of success. The teachers in this study had varying levels of mathematics, 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 mathematics 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 mathematics or science even though it was the subject they were certified to teach. The findings may also inform future teacher educators. Teacher educators may want to customize development opportunities for individual teachers where teachers can develop the specific subject matter knowledge (i.e., physics, engineering, LEGO robotics) that they struggle with the most. The methods used in the study may be able to guide future researchers who wish to capture teachers' subject matter knowledge use and development as it specifically relates to engineering.

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Notes

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[i] The *governor rules machine* is a LEGO creation from the book Brick Layers: Creative Engineering With Lego Constructions. The machine uses a series of spur, crown, and bevel gears to make a contraption that allows the student to crank a handle and transfer the motion 90° in a helicopter-like motion.