DEVELOPING MIDDLE SCHOOL ENGINEERING TEACHERS: TOWARD EXPERTISE IN ENGINEERING SUBJECT MATTER AND PEDAGOGICAL CONTENT KNOWLEDGE

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Abstract

The purpose of this review is to examine various educational constructs and explore links to developing middle school engineering teachers. In our technical society today, learning and teaching engineering is becoming more and more important. National and state standards are beginning to include engineering content standards for K-12 classrooms. If teachers are going to begin teaching engineering they will, undoubtedly, need some preparation before they begin. In this review, I look at subject matter knowledge, pedagogical knowledge, and expertise and discuss how what has already been done in other fields such as math and science education can be used to inform future development of teaching engineering in the middle school classroom. Conclusions about how subject matter knowledge and pedagogical content knowledge impact teaching and learning along with insights from expertise literature are used to provide guidance for future research and potential professional development implications.

Introduction

The goal of this review is to consider the research on teachers' knowledge base and expertise to form a framework through which I can look at teachers' development within the content area of engineering at the middle school level. Not much has been written about the knowledge base of teaching or expertise in the domain of teaching middle school engineering. Thus, this review will look mostly at work done in teaching math and science; however, I acknowledge that engineering is a different content area from science or math. The goal of middle school engineering, as I will define it, is to have students understand how to systematically approach problem solving and design solutions using knowledge from not only math and science, but also history, economics, ethics, and so on. Engineering also includes concepts of specific applications (i.e., gears) that incorporate physics and math, but are rarely taught in either subjects.

Engineering is a relatively new discipline being considered in national and state curriculum frameworks and standards to be taught to Kindergarten through Grade 12 students (International Technology Education Association, 2002; Massachusetts Department of Education, 2006a; Massachusetts DOE, 2006; National Research Council, 2005). This is likely a response to an increasing dependence and demand for technology in the world today. As technology—the result of engineering—advances and becomes more and more intertwined in the way the world operates, the pressure to generate new engineers increases. Schools have been transforming into places where students learn about and use new technologies. You are likely to find a computer lab and computer teacher in every school. Learning such technology is certainly valuable and important; however, there are not many opportunities for students to learn or experience engineering. Engineering not only makes the technology around us possible, it is also allows us to put our knowledge to a real and practical use. Engineering in the classroom will allow students to see the value of what they are learning, apply their knowledge to contexts that make sense to them, and be free to create and explore the world around them. It will allow them to engage in the production, and not merely the consumption, of new technologies.

If engineering is going to be taught in the classroom, teachers will undoubtedly require some preparation prior to implementing an engineering curriculum. Few in-service middle school teachers have any engineering experience or background. There are also very few pre-service programs that prepare teachers to teach engineering. Thus, the need for some sort of intervention before teachers are able to teach engineering in the classroom is evident. Before any teacher professional development program is rolled out in the area of engineering, it is important that it be informed by the knowledge base teachers will need to develop. We must first know what is most important in teaching engineering. What makes an expert engineering teacher an expert? What engineering knowledge base must teachers develop and acquire? Then, we must investigate what are the best practices in developing this knowledge and expertise in our teachers. As engineering education evolves, this is an important area for educators to focus on.

Engineering in the K-12 Classroom

Engineering education in the K-12 setting is often misconstrued as "tech. ed." or "shop class," which has a negative connotation compared to engineering as a profession (Wicklein, 2003). For the purpose of this review, engineering education will focus on engineering design and the processes engineers use to design and create technology. There are many different fields of engineering—mechanical, civil, electrical, aeronautical, industrial, software, etc.—all of which have unique content. However, for a middle school or introductory engineering program, the process of engineering is something all of these fields have in common. Each field may not use the same exact process, but, for the most part, engineering is a process to create some technological ends. Engineering is most often defined as:

> The application of scientific and mathematical principles to practical ends such as the design, manufacture, and operation of efficient and economical structures, machines, processes, and systems. (Engineering, n.d.)

The first part of the definition, "the application of scientific and mathematical principles to practical ends…" can be broken down even further. The first phrase, "the application of," is describing a process, a key part of what will be defined as engineering in the middle school classroom. In engineering, you apply science and math to "practical ends." Students apply their knowledge to real-life, contextual problems and situations. This is what is required of people once they complete their formal education and are engaged in society and the workforce, whether it be in engineering or not. However, engineering does not have to be limited to scientific and mathematical principles and can include principles, of history, social science, economics, etc.

The second part of the definition—"…the design, manufacture, and operations of efficient and economical structures, machines, processes, and systems" can also be broken down. This is the subject matter that is most commonly associated with engineering. Bridges, roads, machines, buildings, and computers among others, make up the subject matter within each field of engineering to which you apply the engineering design process. There are many more and different areas within the myriad fields of engineering. The specific subject matter or focus within the field of engineering chosen (e.g., bridge design) will serve as the context for the engineering design process and should be something the students can relate to and find engaging. This area of content should also appropriately apply the math and science concepts the students are learning or have learned. The Massachusetts DoE (2001) has developed a version of the engineering design process to be used in the K-12 curriculum (see Figure 1). The Massachusetts DoE has also named several content areas appropriate for middle school engineering—materials, tools, and machines; engineering design; communication technologies; manufacturing technologies; construction technologies; transportation technologies; bioengineering technologies. These content areas, along with the engineering design process, are what I define as K-12 engineering education for the middle school level.

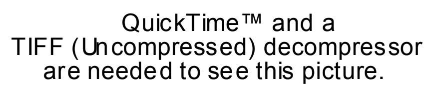

Figure 1: Engineering Design Process (Massachusetts DoE, 2001)

For in-service and pre-service middle school teachers, I assert that the most important aspect of engineering for them to become facile with is the process of engineering or, more specifically, the engineering design process. Not so that they know the steps, but so that they understand how to systematically approach problems and design solutions. I assume that these teachers already have some prior math and science knowledge. They will be able to use this knowledge to choose what types of engineering applications or contexts they will use in their classrooms to teach the process of engineering. To introduce engineering to middle school students, it is not necessary to cover specific types of applications. Rather, you want the students to better understand what engineering is all about and how they can work as engineers in the classroom.

What exactly will teachers need to be prepared to teach engineering in their classrooms? There is already much debate in math and science as to what preparation teachers need—subject matter, educational methods, degrees, experience (Darling-Hammond, Berry, & Thoreson, 2001; Goldhaber & Brewer, 2000). However, what is evident from these studies is that some subject matter preparation and educational methods do lead to better student performance. For engineering, it is unlikely teachers have received any of this prior preparation. As Monk (1989) stated in his look at teacher education, it is unlikely that content specialists in math and science would choose to teach as the salaries in other fields are more attractive than those in teaching. It seems even more likely that people with engineering degrees will choose the higher paying positions over teaching. Thus, it may be difficult to require an engineering degree for someone to teach engineering. Will teachers' preparation in science and/or math be sufficient for them to teach engineering? How much additional specific engineering subject matter preparation will they need? These are questions I will not be able to answer through this review of the literature. However, this review of the literature may be able to provide direction and support for future research in preparing teachers to teach K-12 or middle school engineering.

Breaking Down the Teacher Knowledge Base

To understand how to prepare teachers to teach engineering, a potentially new concept or process for many teachers, it is first important to look at the knowledge base that makes up teaching, beyond engineering or any other specific field. In other words, what do teachers need to know to be able to teach a subject, any subject, to their students? Shulman (1987) organizes a teacher's knowledge base into the following categories:

- Content knowledge;
- General pedagogical knowledge, with special reference to those broad principles and strategies of classroom management and organization that appear to transcend subject matter;
- Curriculum knowledge, with particular grasp of the materials and programs that serve as "tools of the trade" for teachers;
- Pedagogical content knowledge, that special amalgam of content and pedagogy that is uniquely the province of teachers, their own special form of professional understanding;
- Knowledge of learners and their characteristics;
- Knowledge of educational contexts, ranging from the workings of the group or classroom, the governance and financing of school districts, to the character of communities and cultures;
- Knowledge of educational ends, purposes, and values, and their philosophical and historical grounds. (Shulman, 1987, p. 8)

It is clear from Shulman's categories, above, that teaching requires much more than knowing the content of a subject well. A teacher draws upon a wide range of knowledge to teach a student. For example, take the problem 2 minus 5. What is the answer? Negative 3, of course. Now explain this to a second grader, to a college English major, to your grandmother. Each will require a different approach or explanation to best understand this concept, as each has their own prior knowledge and capabilities. Ball and

Bass (2003) note that a teacher's own ability to solve such a problem is not enough, and they have to be able "to inspect alternative methods, examine their mathematical structure and principles, and to judge whether or not they can be generalized" (p. 7). Both Shulman (1987) and Ball and Bass (2003) submit that teaching requires much more than knowing the subject, and calls on a knowledge for teaching, which is much more complex. These teacher knowledge types or categories are often overlooked and replaced with the notion that the better a teacher knows the content, the more college-level courses they have taken in the subject, the better they will teach the content. It is important that when teachers are prepared to teach engineering, that more than just subject matter knowledge is developed.

Gess-Newsome (1999), in her review, shows how Shulman's categories above were later refined by Grossman into subject matter knowledge, general pedagogical knowledge, knowledge of context, and pedagogical content knowledge. The first three knowledge bases (see Table 1 below) match up well between Shulman's list and Grossman's condensed list, while Grossman's idea of pedagogical content knowledge subsumes Shulman's last four knowledge bases, assuming these are specific to a content area. Pedagogical knowledge roughly captures the second two in Shulman's list and pedagogical content knowledge captures the rest.

Table 1: Teacher knowledge bases according to 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	

Gess-Newsome (1999) also created the models in Figure 2 that highlight how pedagogical content knowledge becomes the overlap of the subject matter, pedagogical, and contextual knowledge bases. She then defines pedagogical content knowledge as what is necessary for classroom teaching. Her model not only includes the knowledge included by Shulman and Grossman, but also takes it a step further to show the interaction between all the knowledge bases. With no clear definition of what specific pieces or kinds of knowledge pedagogical content knowledge consists of, I've attempted to pull together some of the common examples or themes from across the literature. Table 2 describes some of these examples.

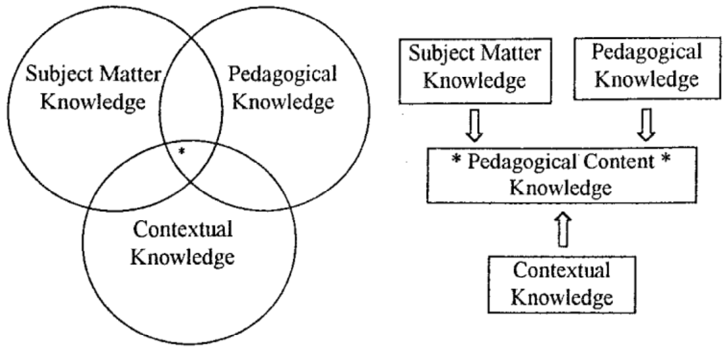

Figure 2 Gess-Newsome's (1999, p. 12) models of teacher knowledge

Table 2: Pedagogical content knowledge components

Components of pedagogical content knowledge	
Pedagogical content knowledge	Knowing students - knowledge of what misconceptions (content specific) students have, what they struggle with, how they are unique, etc. (Driel, Verloop, & Vos, 1998; Magnusson, Krajcik, & Borko, 1999; Shulman, 1986; Veal, Tippins, & Bell, 1998)
	Real world examples - real world examples the teacher uses to link what is being taught in the lesson to examples the students can relate to. (Davis, 2003; Magnusson, Krajcik, & Borko, 1999; Shulman, 1986)
	Appropriate examples - examples a teacher uses that are appropriate for specific children or learning styles and the specific content. (Magnusson, Krajcik, & Borko, 1999)
	Managing the lesson - methods of managing the lesson that are specific to the content (i.e. engineering) being taught. (Shulman, 1986)
	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)

Teaching engineering, as previously defined, will require a teacher to draw upon much more than subject matter knowledge. The hands-on, collaborative nature of engineering design projects requires knowledge and skills unique to engineering. Engineering problems commonly have multiple solutions that are often equally valid. Unlike math and science that, traditionally, have correct and incorrect answers, engineering calls for solutions that can be unique for each student. Teachers will need to develop skills to assess how their students are progressing in their understanding of engineering without simply using a test or correct results from a lab experiment testing some pre-defined law or theory.

Looking at the teacher knowledge base outlined by Grossman (1990) in Table 1, there are four different knowledge bases. The second and fourth knowledge bases, general pedagogical knowledge and knowledge of contexts, are both important bases of knowledge, but are not specific to engineering, and, for this reason, will not be included in this review. This review will focus on the subject matter knowledge and pedagogical content knowledge of teachers. These two knowledge bases were chosen because they are both specific to a particular subject. There is very little literature on these two knowledge bases within the engineering discipline. Thus, the review will focus on studies in the sciences and math. Choosing these two subject areas is quite appropriate given that the definition of engineering includes "the application of scientific and mathematical principles to practical ends…" (Engineering, n.d.). We will first look at the subject matter knowledge of teachers and then at the pedagogical content knowledge of teachers.

A Look at Subject Matter Knowledge

It is fairly obvious that a teacher should have strong subject matter knowledge in the subject they teach. Again, in the subject of engineering, there is little agreed upon content that makes up this subject area especially as would apply to a middle school curriculum. There are many disciplines within engineering (e.g., electrical, mechanical, civil, nuclear, etc.) and each has its own content focus. However, there has been little research regarding the development of specific engineering subject matter knowledge. Thus, the studies reviewed in this paper will mainly look at teacher subject matter knowledge in science and math contexts, which may help guide future exploration and research regarding developing teachers' engineering subject matter knowledge.

From the literature, there are mixed results regarding the correlation between a teacher's subject matter knowledge and a student's performance. A comprehensive review of the literature by Wilson and Floden (2003) revealed studies showing a negative or no correlation between teachers having more degrees, more preparation, or better test results and their students' gains, and others showing a positive correlation. Many studies have been designed to gage the effect of teachers on student achievement (reviewed in Rowan, Correnti, & Miller, 2002). These too show mixed results. While there may not be agreement regarding exactly how much subject matter knowledge would qualify a teacher to teach a subject or to what extent it will impact a student's school achievement, it is, nevertheless, knowledge a teacher has to have, at some level, in order to teach a subject. It would be difficult, if not impossible, to teach someone how to divide fractions if you, yourself, did not know how to divide fractions.

For this review, I am not as interested in how the number of degrees or how teachers' certification impact students' gains, but more interested in how a teacher's knowledge of the subject matter impacts their students and teaching. To this point, there are no defined certification requirements for someone to teach engineering like there is in math or science. Also, courses taken in college may not accurately represent the depth of a teacher's understanding for the more basic middle school principles in that subject. For these reasons, in this review I focus on studies investigating how a teacher's subject matter knowledge impacts their ability to foster learning in students and how it affects their perceptions of their own expertise. First, I will briefly describe the research studies I reviewed and then discuss the results from them.

Studies Focusing on Teachers' Subject Matter Knowledge

The following are the main studies that have focused on the impact of subject matter knowledge on math and science teachers teaching. Ma (1999) conducted a comparative study of 23 United States (U.S.) and 72 Chinese elementary school teachers' understanding and teaching of elementary mathematics. In this study, Ma looked at how the in-depth understanding of elementary mathematics compared among 23 better than average (by U.S. standards) U.S. teachers compared to that of the 72 Chinese teachers of all levels. The U.S. teachers in this study were considered by Ma to be "better than average" because they had taken more high-level mathematics courses in their teacher preparation studies than the Chinese teachers.

Ball (1990) conducted a study focusing on the mathematics subject matter knowledge of pre-service elementary and secondary mathematics teachers. Ball used results collected from questionnaires and interviews of 252 prospective teachers (n=217 elementary education majors, n=35 mathematics majors) that were part of the Teacher Education and Learning to Teach Study (TELT). The prospective teachers were all entering formal teacher education programs at five different sites: Dartmouth College, University of Florida, Illinois State University, Michigan State University, and Norfolk State University. She used just one part of this large study that focused on mathematics to understand the mathematical understandings prospective teachers brought from their pre-college and college mathematics experiences.

Davis (2003) conducted a study where she analyzed one prospective elementary teacher's knowledge in science and how it changed as she developed an instructional unit on the concept of light for fourth grade students. Davis conducted the study during the third semester of a small undergraduate teacher preparation program. Data consisted of semi-structured, 90-minute interviews before, during, and after the course, written work for the course (e.g., her instructional plan), numerous mini-interviews within the course, and email correspondence. Davis focused on specific science concepts in her interviews and used these sessions to have the prospective teacher (Val) explain in some detail what she knew about the topic and how she could relate it to her students' real life experiences.

Beijaard, Verloop, and Vermunt (2000) conducted a study where they investigated secondary school teachers' perceptions of their professional identity as subject matter experts, didactical experts, and pedagogical experts. The study looked at 80 experienced teachers who filled out surveys about their background information and their perceptions of themselves as teachers both in the present and when they first began teaching. These teachers were selected from 12 secondary schools in the Netherlands, had to have at least four years of teaching experience, and were chosen with the assistance of school administrators. From these surveys, the researchers were able to see if the teachers classified themselves as subject matter experts, didactical experts, or pedagogical experts. They were also able to see how the teachers' perceptions had evolved since they began teaching.

Depth vs. Breadth

What is more important, the amount a teacher knows about their field or the depth of their understanding of the basics? For example, is it better for an elementary school math teacher to have a deep understanding of basic math—addition, subtraction, multiplication, division, fractions, etc.—or to have knowledge of algebra, trigonometry, and calculus? Ma (1999) explores this question. What Ma (1999) found was that the Chinese teachers had a much deeper understanding of the basics, even though the U.S. teachers had taken more advanced courses in college. The Chinese teachers could think beyond the rote formulas for division of fractions, multi-digit calculations, etc., while many of the U.S. teachers were content with passing along the "rules" of basic arithmetic. Ma reported that the lack of depth in the subject matter knowledge of the U.S. teachers restricted their capacity to promote conceptual learning among students. Ball and McDiarmid (1990) also argue that a pupil will only be able to gain as deep an understanding of the subject matter as their teacher has.

Ball's (1990) study further revealed a lack of depth of mathematics understanding amongst prospective teachers enrolled in U.S. teacher education programs. Pre-service teachers were able to perform mathematical tasks such as dividing 1 ¾ by ½, but less than half of both prospective elementary and secondary teachers were able to generate an appropriate representation to explain the underlying mathematical principles in the problem. Of the teachers that were interviewed (elementary n=25, secondary n=10) none of the prospective elementary and less than half of the secondary teachers were able to give completely appropriate representations or explanations, and Ball noted that even the correct answers did not come easily. Ball surmised that the prospective teachers prior mathematics experiences only required them to memorize rules and remember the methods for certain calculations rather than requiring a deeper understanding of some of the basics (i.e., division). While the mathematics majors had more success with generating representations for division problems, Ball submitted that this may only be because they have been engaging in mathematics coursework more recently than the non-math majors. It appears that *breadth* of knowledge can impact one's *depth*, however, *depth* of fundamental mathematics (i.e., division) may be better addressed through courses focusing on the nature of, understanding of, and meaning of these fundamentals.

Davis' (2003) study revealed similar results. Davis' teacher, Val, had a great *breadth* or amount of knowledge around the concept of light. Val could correctly identify sources of light, how light interacts with the surrounding objects, and how our eyes see these objects and colors. Val was able to correctly link these science concepts to potential real-world experiences of her students in her instructional unit. Val's breadth of subject matter knowledge was certainly important in her development of her instructional unit; however, as Davis points out, "some of Val's instruction is flawed even when her understanding is strong" (Davis, 2003, p. 40). There were times when Val was accurate with her scientific principles, but when she attempted to link them to real world examples for her students, she ended up linking to things that were only "marginally related, scientifically" (Davis, 2003, p. 40). Here the depth of her knowledge is not sufficient to transfer to real-world contexts that will better guide her students' learning.

Ma (1999) also illustrates how depth of understanding contrasted between the U.S. and Chinese teachers for seemingly simple concepts. The teachers with a deeper understanding, mostly the Chinese teachers, had a clear idea of what the simplest form of a certain mathematical idea is and were then able to break it down to any level for their students. 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 [multi-digit multiplication]" (Ma, 1999, p. 52). Without the clear and deep conceptual understanding of the elementary procedure, teachers, mostly the U.S. teachers in this case, were unable to relate the procedure to something else because all they could do was give the formula or the steps for completing the algorithm.

Relating back to engineering in the K-12 classroom, a depth of subject matter knowledge may support teachers in strengthening their students' understanding. A superficial understanding of the engineering design process (Figure 1) may lead to teachers just relaying the steps of the process. Ball's (1990) study illustrated that a student's question of "why?" may simply be answered with, "because that's the rule." The students would then be left with a recipe-type approach rather than learning the engineering design process as a systematic, iterative approach to problems in order to achieve efficient and appropriate design solutions. As seen in the area of math from Ma's (1999) study, teachers of engineering may not appropriately or effectively break the design process or the engineering concepts into their simplest form for students to more easily understand. It's important for students to understand the iterative process of engineering design, consider multiple features and constraints, and communicate designs and solutions (McKenna & Agogino, 1998), and be able to develop these kinds of skills beyond just memorizing the steps of the process. However, teaching engineering is not solely teaching the engineering design process. There are numerous engineering concepts that would be taught in conjunction with the process. For example, the concept of gears may be included in a transportation vehicle design problem. The concept of gears includes the mathematical principles of ratios and circumference and the physics principles of force and motion. A teacher needs to break gears down into these principles instead of simply saying, "the rule is that when the 10-tooth gear makes one rotation, the 5-tooth gear makes two rotations." With the myriad disciplines within engineering this is no simple or trivial base of knowledge.

Teacher Efficacy and Subject Matter Knowledge

Self-efficacy is one's belief in oneself that one can affect change (Bandura, 1997). Bandura found that "people's level of motivation, affective states, and actions are based more on what they believe than on what is objectively true" (1997, p. 2). Tschannen-Moran, Hoy, and Hoy, (1998) situating self-efficacy in a teaching context, described it as a "teacher's belief in her or his ability to organize and execute the courses of action required to successfully accomplish a specific teaching task in a particular context" (p. 233). Hoy and Davis (2006) outline how a teacher's self-efficacy impacts the performance of his or her students. They describe teacher's self-efficacy as a cyclical process where high self-efficacy leads to teachers being more diligent in their preparation, leading to better student outcomes, and, thus, higher self-efficacy. The opposite is also true, where low self-efficacy leads to less diligence in preparation, leading to poor student outcomes, leading to lower self-efficacy. Hoy and Davis (2006) describe a number of factors that influence a teacher's self-efficacy—one being their subject matter expertise or mastery experience as Bandura (1997) more generally states it. Ball (1990) noted in her study that the teacher's views of their own subject matter knowledge in math greatly affected their confidence and control in their interviews. Many of the prospective elementary teachers were anxious and felt they did not have the innate abilities to do well in math and generally avoided the subject. Ball (1990) concluded that “teachers’ feelings are *part* of the way they participate in and understand mathematics, *not* a separate affective dimension called “attitude”, and are a critical area of focus for teacher education” (p. 462). The study conducted by Beijaard, Verloop, and Vermunt (2000) addresses the idea of subject matter expertise as they investigate teachers’ perceptions of their teaching expertise.

Beijaard, Verloop, and Vermunt’s (2000) investigation looked at teachers who consider themselves subject matter experts. Teachers’ explanations of why they considered themselves subject matter experts and why they considered that they couldn’t be a teacher unless they had the subject matter expertise often included, “that subject matter is the basis for a teacher's authority and for being taken seriously by students” (Beijaard et al, 2000, p. 758). This type of statement appears to be directly related to a teacher’s self-efficacy, in that students would not take them seriously, and if they were not taken seriously, they would not be able to affect change in their students. The following is a statement from someone who perceived him or herself as a didactical expert as opposed to a subject matter expert: “Being a subject matter expert is not relevant to me. In general, the teacher knows infinitely more than the student,” (Beijaard, et al, 2000, p. 758). Even in this statement, from a didactical expert, the teacher puts a great emphasis on his or her own knowledge as compared to his or her students’. This supports the idea that a teacher must have strong subject matter knowledge, or at least stronger than his or her students', to have high teacher self-efficacy, which, as Hoy and Davis (2006) described, leads to a cycle better preparation and better teaching.

Another interesting finding from Beijaard, Verloop, and Vermunt's (2000) study is how the teachers perceived themselves as first-year teachers. Though the researchers did question the validity of this retrospective data, it was interesting to see a significant shift from subject matter experts as beginning teachers to either didactical or pedagogical experts as experienced teachers. Without much experience, teachers appear to rely heavily on their subject matter expertise in the classroom, but they then develop didactical and pedagogical expertise as they gain teaching experience. If the teacher self-efficacy is indeed cyclical as Hoy and Davis (2006) describe, then it appears a beginning teacher with strong subject matter knowledge will be more diligent in their lesson preparation than someone with weak subject matter knowledge. Over time, through this cycle, the teacher with stronger subject matter knowledge will develop stronger didactical and pedagogical knowledge. This, again, emphasizes the variety of knowledge that makes up a teacher's knowledge base.

Teacher self-efficacy is an important consideration in the preparing middle school engineering teachers. Cejka (2005), in her study, reported that teachers involved in her professional development workshop were uncomfortable and at times frustrated with either not knowing or with there not even being a "right" answer for the open-ended engineering design projects they were working on. The nature of engineering is that there are, often, no a priori answers, and, instead, there are many different solutions to engineering problems. Teachers may feel like they have less self-efficacy as they start such open-ended design problems with their students, and will rely on the subject matter knowledge they have from math or science that may not quite fit. Back to Hoy and Davis' (2006) cyclical process, the teachers with low self-efficacy won't prepare for lessons as well as teachers with high self-efficacy and would take longer to develop their knowledge base for teaching engineering. The teacher's engineering knowledge development would slow or even stop if they chose to go back to math or science activities where they had higher self-efficacy.

Subject Matter Knowledge Summary

A review of the literature leaves unanswered specifically what subject matter knowledge a teacher will need to teach engineering. However, the literature supports the notion that the knowledge base of subject matter will need to be addressed as schools and districts implement engineering curricula. The study of subject matter should go beyond whether or not a teacher can simply answer or solve an engineering problem. In math, Lampert (1986) broke down the subject matter of math into intuitive knowledge, computational knowledge, concrete knowledge, and principled knowledge. She noted that these are all necessary to teach and it is the ability to connect all these types of knowledge that constitutes teaching mathematics. Similarly, Ball and Bass (2003) highlighted the 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). In a study I conducted (Hynes, in press), there was a clear difference in the subject matter knowledge between the teachers in the study. I administered a knowledge assessment based on the Massachusetts Comprehensive

Assessment System (MCAS) questions for eighth graders on engineering and technology. There was a clear difference in assessment scores among teachers with engineering backgrounds and those with only math or science backgrounds. The only teacher who scored perfectly on both the pre- and post-assessment had a Bachelor's degree in engineering. Strong math and science subject matter knowledge helped the other teachers learn and grasp the curriculum; however, from my own observations, the teachers without an engineering background were not delivering the content within the curriculum to their students. It is clear, that the subject of engineering will need to be broken down as Lampert (1986), Ball and Bass (2003) have done for math. This leaves us with the question, what is enough engineering subject matter knowledge for a middle school teacher and what constitutes this subject? This question cannot adequately be answered without further research; however, I have proposed the following coursework based on Massachusetts D.o.E.'s (2006b) teacher certification requirements, a few college/universities' engineering degree requirements (Dartmouth College, 2007; Tufts University Department of Mechanical Engineering, 2006; University of Maine, 2007), and the Accreditation Board for Engineering and Technology's (2006) requirements for engineering program accreditation to be "enough" engineering subject matter knowledge for a middle school teacher.

First, any teacher with a Bachelor's degree in any accredited college engineering program would have completed adequate coursework. As stated earlier, it may be difficult to require such a degree and expect to find individuals willing to pass on lucrative engineering jobs to complete further coursework to become teachers, thus, we may want to consider less stringent requirements. Based on the teacher certification requirements of Massachusetts D.o.E. (2006b) and what is outlined in the Massachusetts D.o.E. (2006a) middle school curriculum frameworks, a Bachelor's degree in math or a science along with further engineering coursework should be adequate. The important subject matter concepts or topics that are integral to teaching middle school engineering include knowledge of:

1. Engineering design and the technology development process
2. Basic concepts of engineering and technologies from various fields (i.e., mechanics, electrical circuits, manufacturing technologies, communications systems, or computer programming)
3. Materials (e.g., advantages/disadvantages of metals, plastics/polymers, ceramics or organic materials)
4. The profession and what engineers do
5. The requisite fundamental math and physics/science concepts

My proposed undergraduate coursework would be similar to majoring in a math or science and minoring in engineering. Typical undergraduate minors in a field consist of 4-8 courses within that field (Dartmouth College, 2007; Tufts University Department of Mechanical Engineering, 2006).   Coursework would include a minimum of 4 courses from the following:

1. Engineering science courses, 1-2 of such courses (i.e., fluid mechanics, thermodynamics, statics, or electronic theory)
2. Engineering materials courses, 1-2 such courses
3. Engineering design or project based course, minimum of 1 such course

Coursework like this does not sufficiently address the need for depth of knowledge in the basic engineering principles. However, given what is currently being taught, this may be the best starting point. Future research in this developing field should include what types of courses and knowledge teachers will rely upon to teach this content and be able to answer the students' questions of "why?"

A Look at Pedagogical Content Knowledge

In this section, I will review studies looking at teachers' pedagogical content knowledge. The studies, which I will briefly summarize, look both at the development of pedagogical content knowledge as well as its impact on student learning. From these studies, I have chosen three areas (knowing the students, strategies for teaching, and pedagogical content knowledge development) to focus the discussion on. The first two come directly from Table 2 while the third area looks at how this knowledge base is developed. Appleton describes science pedagogical content knowledge as follows:

> Science PCK [pedagogical content knowledge] is a form of teacher knowledge transformed from other forms of teacher-knowledge (Magnusson et al., 1999). It has inherently close links to the teacher's science content knowledge, and is developed through the teacher's own experiences and science teaching practices, as well as the recommendations from colleagues' experiences. In developing science PCK, teachers draw on a range of other forms of teacher knowledge, such as knowledge of curriculum, context, general pedagogy, and children. (Appleton, 2003, p.4)

The review of this body of literature will touch on a number of the qualities of pedagogical content knowledge Appleton includes in his description.

Studies Focusing on Pedagogical Content Knowledge

Veal, Tippins, and Bell (1998) conducted case studies on two prospective secondary physics teachers where they looked at the development of their pedagogical content knowledge. The two prospective teachers, Maggie and Tami, were followed in their secondary science methods class and in their subsequent student-teaching field experience. The researchers used structured and semi-structured interviews as well as documents and other artifacts pertaining to their science methods class as data for this study. Maggie and Tami taught concepts of linear motion and thermodynamics over the course of their field experience.

In a post hoc study, Appleton (2003) used data from two previous studies to examine how beginning teachers with limited science pedagogical content knowledge coped with trying to teach science and to what extent the construct of pedagogical content knowledge can provide a basis for understanding this coping behavior. The first study he analyzed from was an investigation of nine beginning primary school teachers from a variety of schools teaching a variety of grade levels (1-6). Semi-structured interviews and the field notes from classroom observations of these teachers were used to construct a picture of these teachers' science teaching practices. The second study also used semi-structured interviews and classroom observations, but this study included twenty experienced primary school teachers (grades 1-6). The focus of this study was to examine science lessons that worked well for these teachers and to establish what about these lessons made them work well. Appleton then pulled the data from these two studies together to, first, investigate what strategies beginning teachers used to compensate for their limited science pedagogical content knowledge and, second, to learn what practices led to activities that worked among the experienced teachers.

As part of a longitudinal research study, van Driel, Verloop, and de Vos (1998) conducted a study investigating how teaching experiences impact teachers' science pedagogical content knowledge. The research team conducted an in-service workshop attended by 12 secondary school teachers with an academic background in chemistry and more than 5 years of teaching experience. The workshop sessions were recorded on audiotape and relevant pieces were transcribed and analyzed. Teachers' written responses to assignments and questionnaires as well as the responses of their students to the assignments in the experimental course also served as data for the researchers. The workshop focused on the chemistry topic of chemical equilibrium.

Viiri (2003) looked at experienced Finnish polytechnic engineering teachers as they taught first-year engineering students taking a civil engineering course. In this study, Viiri followed three experienced teachers and studied their notions about their students' conceptions. The research team gave both the teachers and students a questionnaire testing their understanding of the topics in the course. The teachers were asked to describe in writing their expectations for the students answers to the questionnaire. The teachers were then given their students' answers and the research team observed their reactions to seeing their students responses.

Knowing the Students

Knowledge of students is one of the knowledge bases Shulman (1987) outlines in his knowledge bases for teaching (see Table 1). In earlier work, Shulman also included this knowledge base as something that, "should be included at the heart of our definition of needed pedagogical knowledge" (1986, p. 10). More explicitly, this knowledge of students includes understanding their current knowledge and cognitive abilities, their common misconceptions or difficulties with certain topics and ideas, contexts and examples that appeal to them, etc. (Berliner, 1986, 1994; Gess-Newsome, 1999; Shulman, 1986). The studies reviewed in this section address some of the issues in teachers' knowing or not knowing their students.

First, as Veal, Tippins, and Bell (1998) observed in their study, limited pedagogical content knowledge leads to a more teacher-centered or procedural view of teaching. This was the approach to teaching described before the teachers—Maggie and Tami—had their field experience. Maggie described the teacher as having the control during the lecture or lesson. She was not aware of the extent to which the students would influence the course of a lesson or discussion. The procedural view they described was mostly based on the content or subject matter they would be teaching. With limited pedagogical content knowledge, Tami and Maggie relied more heavily on their subject matter knowledge. Davis (2003) similarly noted that even with strong subject matter knowledge, the teachers' inability to link the subject matter to real-life examples and contexts the students understand and are interested in will limit student learning. This, of course, calls for some knowledge of their students. Furthermore, if the teachers' subject matter knowledge lacks depth, they may be very limited in what they can actually teach or have their students learn (Hammerness et al., 2005; Loucks-Horsley & Matsumoto, 1999; Ma, 1999).

Then, as Maggie and Tami both began their field experience, they came to realize the subtle, real-life aspects that contributed to teaching and the learning environment (Veal, Tippins, & Bell, 1998). The researchers described Maggie and Tami as beginning to develop topic-specific pedagogical content knowledge as they gained field experience. For example, after witnessing another teacher present an analogy of a waterfall to explain heat flow, Maggie was able to critique the analogy. She thought it was a good analogy, but was introduced too soon to the students. This demonstrates that Maggie had shifted from her teacher-centered view to a more student-centered view of teaching. Appleton (2003) similarly notes that teachers learn from their interactions with students, which is, in turn, how they begin to develop their pedagogical content knowledge.

Driel, Verloop, and Vos (1998) provide a concrete example of a teacher learning from his students and developing pedagogical content knowledge in the classroom. The researchers observed during a classroom discussion a group of four students explaining their ideas of the chemical reaction carried out in an earlier classroom experiment. The teacher listens to the students explanations and witnesses two of the students relating the experiment in such a way that the other two students come to understanding as one remarks, “Oh! Now I see” (Driel, Verloop, & Vos, 1998, p. 687). In this case, the teacher is able to see the problem the two students were having in understanding through the argumentation of the group. From this interaction, the teacher was able to extend his pedagogical content knowledge with knowledge of specific student difficulties and strategies to address similar difficulties in the future.

While the experience of teaching itself does allow a teacher to learn about their students from their students, it may not be enough. Viiri (2003), in looking at experienced teachers, found that through their experience, these teachers were successfully able to predict which problems on a test their students would have the most difficulty with. They were even able to correctly predict many of the types of incorrect answers the students would give. On the surface, it appeared that the teacher knew the students capabilities quite well. However, Viiri's study included a section for the students to explain their reasoning for their answers. When confronted with this information, the teachers were astonished with some of the misconceptions and misunderstandings their students voiced. Viiri saw this is a major concern and a critical limiting factor in successful teaching. If teachers are unable to truly understand how students are constructing their conceptions, how can they guide them to the proper conceptions. Most telling in this study were the teachers' predictions of their students' performance. The teachers predicted the students' mean score to be 58.25%, which was very close to the students' actual mean of 54.17% (Viiri, 2003). Less than a 60% success rate appears to be an indication that the students are either not adequately learning the concepts at hand or not being assessed properly. It is not sufficient for teachers simply to understand what students know or do not know. It appears that teachers don't know why or how the students have less than a 60% success rate. Teachers need to begin to understand students' reasoning and thinking to assist students in constructing the concepts accurately.

Student-centered, constructivist approaches to teaching are highly dependent on a teacher's knowledge of their students. Veal, Tippins, and Bell's (1998) and Driel, Verloop, and Vos' (1998) studies both illustrate that experience is a necessary though not sufficient way for a teacher to fully understand how students are constructing their knowledge. This becomes especially true in an engineering classroom. Teaching engineering often includes the use of open-ended design projects where students design and create solutions for problems. Without robust assessment tools, these projects may, on the surface, appear to exemplify students' learning, but may hide or cover student misconceptions or deficiencies. Teachers need to be able to see beyond these projects and assess where their students are throughout the design experience.

Strategies for Teaching

As Gess-Newsome (1999) illustrates in her models (see Figure 2), pedagogical content knowledge is necessary for teaching. Proper knowledge of students, from the previous section, is certainly one necessary component. This section will highlight some of the specific teaching strategies observed and recorded in the studies. Teaching strategies are, for this purpose, defined as things teachers do in the classroom that aid them in fostering a student's understanding. Appleton's (2003) findings support this notion of pedagogical content knowledge being necessary to teacher. He found that teachers with limited pedagogical content knowledge and, thus, limited strategies for teaching a particular science topic, would often avoid or postpone teaching the topic. With teaching strategies that worked to help students understand, the teacher did not avoid the topic.

Recognizing, using, or creating real-world, contextual examples that students can relate to is one such effective teaching strategy. Earlier in the section *Depth vs. Breadth,* I noted Ma's (1999) observation that depth of subject matter knowledge enables a teacher to break down a topic to its simplest forms. Often, this then allows the teacher to relate this more simple view to an example that the students may better understand. Davis (2003) alludes to her teacher's—Val's—ability to create valuable real-world links for her students and notes this is a powerful strategy for Val. Appleton (2003) notes that this strategy need not solely depend on a teacher's ability to create these real-world examples. He observed teachers using curriculum materials with "built-in" examples that, for a teacher with less experience with a particular topic, gave them the confidence and necessary material to guide their students through an activity. Again, this strategy of real-world, contextual examples harks back to the underpinnings of constructivism. A real-world, contextual example can provide an opportunity for students to assimilate the new concept or idea into what they already know, as they construct new knowledge.

Classroom discussion is a strategy teachers may employ to allow students to "discover" and "invent" 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)

However, she argues that within this traditional view, there is no "process of coming to know" (Lampert, 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 does not reduce the role of the teacher, instead it calls 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). Driel, Verloop, and Vos (1998) illustrate two facets of the effectiveness of classroom argumentation in their observation of a teacher from their study. The first facet was that the students, through discussion, were able to come to know and understand the scientific principle at hand. The second facet was that the teacher gained insight into his students' thought processes and would better guide future classroom discussions with that particular class as well as future classes. Veal, Tippins, and Bell (1998) observed that as teachers gained experience, they were able to see more and more the importance of students voicing their ideas and providing some direction for the discussion and exploration of scientific principles. Because engineering cannot be seen as presenting or having "truths" or right answers, and instead focusing on designing within constraints (Wulf, 2002), classroom discussion may be a valuable strategy in an engineering classroom. Students can propose designs or solutions, argue for their validity, formulate new ideas or change existing ones from feedback, as they create solutions that may never be judged as being "right" or "wrong."

Pedagogical Content Knowledge Development

One common and, likely, obvious theme across the knowledge base of pedagogical content knowledge is that teachers slowly and gradually develop this body of knowledge. As outlined in Table 2, the types of knowledge that constitute pedagogical content knowledge are not something quickly or easily acquired from a book or a single class. Much of what makes up pedagogical content knowledge is learned in classroom interactions with students, from conversations with peers, happenings in the surrounding world, and within the culture or context one lives in. The teacher then constructs their own pedagogical content knowledge from their own distinct experiences and education. In this section, we will further explore how the pedagogical content knowledge studies reviewed in this paper illustrate or highlight the gradual construction or development of a teacher's pedagogical content knowledge.

Veal, Tippins, and Bell (1998) observed a distinct, phase-like process of development among the teachers in their study. First, they recognized that with their teachers—Tami and Maggie—the development of pedagogical content knowledge was gradual. It took time and could not necessarily be given to or pushed upon the teachers. They also realized that the development was non-linear. The teachers would go from one conception or belief to another instantaneously. For example, the teachers began with a very teacher-centered or procedural view of teaching before their teaching field experience. Given the opportunity to teach in the classroom, they suddenly acquired a new perspective where the student was at the focal point of the classroom or lesson. Veal, Tippins, and Bell refined their findings and created a phase-like developmental view of their teachers' physics pedagogical content knowledge. They broke the development of this knowledge into the following six phases:

1. Prospective science teachers were able to integrate the curricula, textbooks, and resources into coherent lesson plans.

2. Prospective science teachers showed an increased differentiation in how they viewed the teaching of physics or chemistry.

3. Prospective science teachers encountered a perturbation that created some sort of dissonance in their beliefs of how to teach chemistry or physics.

4. Participants had the opportunity to reflect on their beliefs, the content knowledge, and any perturbations.

5. Prospective science teachers wrestled with conflicting beliefs by instructing outside of the cooperating teacher's paradigm when given the opportunity.

6. Prospective science teachers integrated, modified, or developed new personal theories that took into consideration many aspects of the classroom-learning environment. (Veal, Tippins, & Bell, 1998, p. 26)

These phases appear to describe a process similar to that of Piaget's description of equilibration as an interaction between assimilation and accommodation (Bringuier, 1980). The teachers integrate the content into coherent lesson plans (assimilation); then at some point encounter a perturbation that creates some sort of dissonance (disequilibrium) in their beliefs of how to teach; then wrestle with their conflicting beliefs and develop new personal theories for teaching (accommodation). Just as Piaget states, "the transformation is slow," (Bringuier, 1980, p. 45), this development of pedagogical content knowledge "does not occur suddenly" (Veal, Tippins, & Bell, 1998, p. 26).

Driel, Verloop, and Vos's (1998) study provides a situation that could fall into the third phase defined by Veal, Tippins, and Bell (1998). The research team described an interaction that took place between the teachers and students in the experimental classroom that followed the teachers' professional development workshop. In the interaction, the teacher was comparing the idea of a classroom with two doors to the process within a chemical reaction. A student rejected this analogy stating, "But that isn't a chemical reaction!" (Driel, Verloop, & Vos, 1998, p. 686). The teacher, later, saw the flaw in his analogy. This perturbation created a dissonance in the teacher's belief on how appropriate his analogy was, which he had been using for years. This disturbance was not resolved for the teacher by the end of the workshop. This observation not only highlights the importance of knowing students as mentioned in the previous section, but it also illustrates how a teacher's pedagogical content knowledge develops over time and is always transforming "since equilibrium is never attained—thank heavens!" as Piaget stated (Bringuier, 1980, p. 44). With this in mind, you could conclude that a teacher's pedagogical content knowledge development is a never-ending process with no final destination.

Teaching Engineering and Pedagogical Content Knowledge

To summarize this section on pedagogical content knowledge, in the case of engineering, pedagogical content knowledge would include strategies to guide students through the engineering design process, create links from math, science, and engineering to contexts the students can relate to, and knowledge of students' misconceptions or ideas relating to engineering and the engineering design process. Given that the subject matter knowledge of engineering includes principles from math and science, the teaching of engineering relies heavily upon what was stated above as pedagogical content knowledge, which is an area that lacks support or direction from research. As previously mentioned, engineering at the middle school level (in Massachusetts) has a large focus on the engineering design process. Teaching the engineering design process could be done by memorizing steps, or reading examples; however, actually going through the process to engineer something may be the best way for students to understand and learn the process. The framework of constructionism (Papert, 1980), built upon the constructivist theories of Piaget (Bringuier, 1980) that knowledge is constructed by the learner, suggests that not only does one construct knowledge, but learners are more likely or able to construct new ideas or knowledge when actively engaged in "making some type of external artifact" (Kafai & Resnick, 1996, p. 1). It would then make sense that teaching the engineering design process should include students going through the process as they engineer their own product. For a teacher to teach in this sort of environment, they will face challenges that may call for new teaching strategies and methods. They will have to carefully guide students at just the right times, ask probing questions, relate the material to real life contexts, and be able to link the math, science, and other subject matter knowledge to the projects the students are engaging in. Thus, the teacher will need to have subject matter knowledge in engineering and relevant math and science concepts, but teaching the engineering design process will require extensive pedagogical content knowledge specific to the engineering design process and applying the specific content area to the process. For this reason, professional development to prepare teachers in engineering should focus on and provide numerous opportunities for teachers to develop their engineering pedagogical content knowledge, while also providing the opportunity for teachers to learn any subject matter they don't already know alongside these opportunities. Table 3 highlights some fundamental pedagogical content knowledge to teach middle school engineering. When considered together, as a whole, this knowledge is what would be necessary to guide students through an open-ended, engineering design activity that engages students in design and math, science, or engineering principles. The complex nature of both teaching and engineering cannot fully be capture in the contents of Table 3, but they are at least a starting point.

Table 3. Proposed Pedagogical Content Knowledge for Middle School Engineering

Pedagogical Content Knowledge of:	Examples of knowledge
Students	• Common misconceptions (math and science) • Common difficulties (spatial reasoning, multivariate problems/decision-making) • What is engaging and relevant in their lives
Real world examples	• Design activities that are engaging for students • Design activities that contain relevant math, science, engineering content
Appropriate examples	• Examples or analogies students can relate to • Examples/activities appropriately challenging for students level of competence
Managing the lesson/design activities	• Managing students within groups working on unique engineering projects • Managing groups to be on track to complete a fruitful project (balance between not enough and too much guidance or direction) • Assessing projects at various levels of progression
Strategies for student understanding	• Simpler forms of the concept at hand to relate to something students understand • Physical demonstrations that reveal concepts to students • Probing questions that elicit exploration and thought from the students

From Knowledge to Expertise

Up to this point, we have focused on two knowledge bases of teaching. Specifically, we have looked at how subject matter knowledge and pedagogical content knowledge can impact teaching. However, a remaining question is the development of expertise in subject matter and teaching. Subject matter knowledge and pedagogical content knowledge, as described up to this point, are bases of knowledge that we hope teachers will have and further develop. The next question is, then, what separates a novice in these knowledge bases from an expert. Researchers studying expertise are most commonly looking at all the things that separate the novice from the expert in a particular domain. They look at the cognitive abilities, the strategies used to solve problems in the domain, and the varying perspectives novices and experts have to distinguish determining factors that make one an expert and another a novice (Berliner, 1986; Chase & Simon, 1972; M. Chi, Glaser, & Rees, 1982; M. T. H. Chi, 1997; de Groot, 1965). While experience and practice certainly contribute to expertise, they are not solely responsible for the development of expertise (Chase & Simon, 1972; de Groot, 1965). In teaching, the practical experience will help teacher's develop expertise; however, I am interested in looking for themes and patterns in subject matter and teaching expertise that may help guide professional development. Some of the earlier works in the study of expertise focused on chess as the researchers looked see what differentiated master chess players from novices (Chase & Simon, 1972; de Groot, 1965). These works not only provide history for the field, but they also describe some problem-solving processes and knowledge organization concepts that may relate to engineering. Chi, Rees, and Glaser (1982) followed with an excellent body of work surrounding expertise in problem solving in the subject of physics. A number of researchers have also worked in the area of expertise in teaching (Berliner, 1986, 1994; Borko & Livingston, 1989; Leinhardt & Greeno, 1986; Livingston & Borko, 1989; Reuber, Dyke, & Fischer, 1990; Sternberg & Horvath, 1995). I will illustrate from these works in chess, problem solving in physics, and teaching the possible connections to becoming subject matter and pedagogical content knowledge experts in the area of engineering.

History of the Study of Expertise: Expertise in Chess

The study of expertise formally arose out of the seminal work of de Groot (1965). He studied chess players and looked for what differentiated master chess players from novice or beginner chess players. From his studies, de Groot concluded that master chess players and beginners both use the same thought processes. They both considered roughly the same number of possible moves and looked roughly the same number of moves ahead in determining their move. However, the master players were considering better moves and selected moves superior to those of the beginners. He was unable to determine exactly what was qualitatively different about these players' strategies, but did discover that masters were able to recognize and then reconstruct, almost perfectly, a chess move after just 5 seconds of viewing the board. Chase and Simon (1972), guided by the early work of de Groot, further explored what differentiates master chess players from beginners. They conducted experiments to look at chess players' short and long term memory capacities and information processing abilities. They concluded that "perceptual processing—the ability to perceive familiar patterns quickly—as the basic ability underlying chess skill" (Chase & Simon, 1972, p. 267). Master players had a virtual library of moves and situations organized in an efficient and effective way in their minds. They were then able to recognize patterns from the current situation and quickly search that library finding appropriate and successful moves. Upon further investigation, they concluded that the most influential variable in the "organization of a Master's elaborate repertoire of information" (Chase & Simon, 1972, p. 279) is time or practice.

Chase and Simon's (1972) findings for chess players appear to map quite well onto Vincenti's (1990) description of the mental activities that engineers engage in when they design. Vincenti writes that a engineers, "search of past experience with similar situations to find knowledge that has proved useful" (1990, p. 246). Then they identify the patterns, similarities, or differences they see between previous designs and the one they are working on. One step in developing engineering design expertise will be to give teachers opportunities to design and build their repertoire of information from participating in multiple engineering design problems and projects. Engaging in these problems and/or projects will aid in their development of understanding for the engineering design process, the subject matter the problem or project is focused upon, and pedagogical content knowledge.

Expertise in Physics

Chi, Glaser, and Rees (1982) conducted a comprehensive series of experiments to break down the quantitative and qualitative differences between experts and novices in the domain of physics. They reported on eight studies in the domain of physics problem solving: protocols of problem solving, sorting problems, sorting specially designed problems, hierarchical sorting, summaries, elaboration, basic approach, and judging problem difficulty. Of these eight studies, we will focus on the four that are particularly relevant to both expertise in engineering and teaching—the *sorting specially designed problems, summaries, elaboration,* and *basic approach* studies. What made these studies relevant were the ties they had to novices' and experts' organization of knowledge, knowledge base, and approach to solving problems. The four studies not included—

protcols of problem solving, sorting problems, hierarchical sorting, and *judging problem difficulty*—were not chosen because they were either too narrowly focused on specific physics problem solving skills that were not easily transferable to the domain of teaching engineering, or the conclusions from the studies were shorter and less informative.

Sorting specially designed problems was a study where Chi, Glaser, and Rees created 20 physics problems to test their hypothesis “that novices are more dependent on surface features, whereas experts focus more on underlying principles” (M. Chi, Glaser, & Rees, 1982, p. 45). When they asked experts and novices to categorize the problems they indeed confirmed their hypothesis. The novices grouped the problems based on their surface features—velocity problem, had a spring, or had a ramp. The experts, on the other hand, correctly grouped the problems based on the underlying physics laws—conservation of angular momentum, conservation of energy, etc. This inability for novices to see beyond the surface features of problems is quite informative for developing teachers’ engineering subject matter knowledge. A teacher may appear to grasp the concepts and be able to correctly answer questions, but if they do not fully understand the underlying principles they may not be able to guide their students as effectively. This finding is very similar to Ma’s (1999) finding that teachers with a deeper understanding of the concepts are able to break the concept into simpler forms for students.

Their *Summaries* study (M. Chi, Glaser, & Rees, 1982) attempted to capture what physics knowledge the novices and experts had independent of a problem-solving context. In this study, Chi, Glaser, and Rees asked the subjects to summarize the key points of chapter in a physics text. The subjects were given 5 minutes to review the chapter and then 15 minutes to verbally summarize the chapter. The novices were students who had recently completed an introductory physics course with a B average and had used the text being reviewed. The experts were two college professors, a postdoctoral fellow, and fifth year doctoral student. It was no real surprise that the experts' summaries provided more complete information, but they noted that the novices were not even able to master the declarative knowledge of the laws of physics, even with a text in hand. This further supports the idea that the ability to answer a question or solve a problem does not imply mastery or understanding. In teachers' development in engineering, it will be critical to use methods that assess their depth of understanding rather than their ability to answer a content specific question. Again, this relates back to the *Depth vs. Breadth* section of this paper. The experts have a deep understanding of the physics here, while the students, have indeed taken a physics course but are far from a deep understanding. We must not only focus on the number of courses a teacher has taken, but also look at the depth of courses within the specific subject they have taken.

The *Elaboration* study (M. Chi, Glaser, & Rees, 1982) was designed to uncover the different knowledge contained in the schemata of the experts and novices. The subjects were given 20 prototypical physics concepts to explain and elaborate on for 3 minutes. The results revealed that both the experts and novices had a fundamental knowledge of the properties of the problem, but the experts had additional knowledge. The experts had explicit procedures or procedural knowledge on hand when it came to the concepts. "The experts' schemata contain much more knowledge about the explicit conditions of applicability of the major principles underlying a problem" (M. Chi, Glaser, & Rees, 1982, p. 62). For both engineering and teaching, the experts will likely have a "bag of tricks" or procedures that they have developed over time to deal with the myriad problems or challenges they face in their domain. It is these procedures or strategies that will be important to uncover to create a definition of expertise in teaching engineering.

M. Chi, Glaser, and Rees' (1982) *Basic Approach* study looked at how experts and novices approach and choose a method for solving a problem. During this study, the subjects were given a problem and asked to think out loud as they determined their "basic approach" to solving the problem. They were then asked to restate their "basic approach" in one short, simple statement. Then, they were asked to explain what features from the problem led them to their approach. The study revealed the problems' surface features mostly guided the novices, and the novices' responses—features mentioned—were very similar. However, the experts' responses and "basic approaches" varied widely. M. Chi, Glaser, and Rees interpreted this finding as a result of the fact that the experts transformed the literal surface features of the problem into higher order features based on their individual knowledge bases, where the novices had limited higher order knowledge at hand and relied more heavily on the literal surface features in their approach.

In sum, this research in physics expertise points to some important qualities of expert and novice knowledge and schemata. These points appear to be relevant and transferable to both the domains of engineering and teaching engineering, which involve similar demands for problem-solving skills. As expert engineering teachers emerge, we will want to note the engineering knowledge and schemata of these individuals. We will also want to follow M. Chi, Glaser, and Rees' work that highlights how important it is to look beyond the surface to the depth of knowledge and recognize and define what expertise looks like in the subject of engineering. It will be important to look at what separates someone who simply "regurgitates" answers to engineering problems from someone who understands the principles and scientific reasoning behind them.

Expertise in Teaching

Stemming from the work done in chess and physics, scholars began to look at expertise in the domain of teaching (Berliner, 1986, 1994; Borko & Livingston, 1989; Leinhardt & Greeno, 1986; Livingston & Borko, 1989; Reuber, Dyke, & Fischer, 1990; Sternberg & Horvath, 1995). This work can help to define what teachers need to develop and how to go about it as they take on teaching engineering. In order to do this, some model of expertise in this domain must be developed. Sternberg and Horvath (1995) succinctly describe their call for a reconceptualization of teaching expertise to be grounded in "how (a) experts differ from nonexperts, and (b) people think about expertise as they encounter it in real-world settings" (p. 1). They propose "that teaching expertise be viewed as a category that is structured by the similarity of expert teachers to one another rather than by a set of necessary sufficient features… in terms of a central exemplar or prototype (Rosch, 1978)" (Sternberg & Horvath, 1995, p. 1).

As we also saw from the physics expertise work, Sternberg and Horvath voice the need to not just look at "a set of necessary sufficient features," but to also look at the real-world qualities and the individual features that can make up teaching expertise. You can't necessarily rely on experience as defining expertise (Berliner, 1986; Reuber, Dyke, & Fischer, 1990) as there is certain tacit knowledge that is developed and organized quite differently in each teacher's experience. Not every experienced teacher necessarily develops the same amount of expertise in teaching. How can we define expertise in teaching? The following sections organize the scholarly work on teaching expertise to illustrate the differences between expert and novice teachers, as well as to lay the groundwork for defining what expertise in teaching engineering will look like.

Area of focus 1: Repertoire and Routines.

A common theme across a number of studies looking at expert teaching is that expert teachers have a large repertoire of techniques, strategies, and routines that guide their practice. Berliner (1994) reviewed a number of studies where the expert teachers were following set routines in each lesson, frequently used repetitive tasks or methods, and had set patterns for the mood and tone of the classroom. The novice teachers' strategies, on the other hand, varied greatly day to day, and rarely showed a consistent pattern or routine. Borko and Livingston (1989) described expert math teachers' ability to quickly access examples or strategies to reinforce the topic at hand. This ability allowed for effective and efficient lessons. Leinhardt and Greeno (1986) saw that expert teachers had "a large repertoire of routines, usually with several forms of each one" (1986, p. 94). These routines could be adapted to each lesson and helped to increase the time the students were engaged with the material. In reviewing the literature, it was clear that the expert teachers had a consistent plan as well as a well-developed set of strategies and procedures to deal with any student or challenge that should arise. For development purposes, teachers, as they learn to teach engineering, will need to develop strategies and routines as well as opportunities to put them into practice and develop new ones.

Area of focus 2: Knowing the Students.

Similar to the findings concerning the pedagogical content knowledge studies, a number of studies in teaching expertise point to the importance of teachers knowing their students and the teaching setting in order to be effective in their teaching. Berliner (1986) replicated the work of Calderhead who noted that the expert teachers had a different schemata for students than that of the novice teachers. Berliner reported that the expert teachers had a greater understanding of the students they were teaching. They seemed to know the background and history of the students much better than the novice teachers. Berliner (1994) reported in his review on another of his studies where novice teachers focused on the surface features of students—whether they had a learning disability, struggled in math, and other issues that were explicit and more evident—in reviewing various scenarios. This was in contrast to the expert teachers who noted both the surface features as well as other emotional and social features that could be implied from the scenario, but were not necessarily explicit. Borko and Livingston (1989) reported that novice teachers were unable to predict where in the curriculum students would have difficulties and often had to limit or cut off student questions because they were unable to deal with them without further confusing other students. The expert teachers did not have this limitation. This knowledge of students is particularly pertinent to teacher development and it will be important for teachers to learn about the students' cultures and upbringings and how the content may be viewed differently within these contexts in order to find connections between the content and the children's' lives.

Teachers will also need to understand cultural differences that may lead to content-specific misunderstandings.

Area of focus 3: Pattern Recognition.

Expert teachers appear to have a greater ability to quickly and accurately recognize patterns within their students and lessons, which then allows them to shift directions or take a new course of action. That is, expert teachers may recognize that a certain questions from the students is the beginning of a pattern that a concept or idea was not understood. Berliner (1994) titled one of his propositions for expertise in teaching, "Experts have fast and accurate pattern recognition capabilities. Novices cannot always make sense of what they experience," (p. 26). Chase and Simon's (1972) work in the domain of chess also reported that experts recognized and remembered patterns better than novices. They were also able to recognize larger chunks of patterns. Live, in the classroom, these expert teachers are able to analyze what they are experiencing and translate it into actions to take, while a novice teacher may not make sense of all that is going on the classroom and not see the "big picture" or pattern of what is going on. Borko and Livingston (1989) also noted that the expert teachers were quick to improvise during the class as they learned where their students were at. The novice teachers were too narrowly focused on the more salient surface features and were unable to recognize more meaningful patterns throughout the lesson. The post lesson reflections of these teachers focused on the behavior of students, classroom management issues, and their perceived effectiveness, while the expert teachers focused on the students and their understanding. It will be important for teachers' to develop the ability to recognize common patterns and themes that emerge when teaching engineering content. In working with middle school students as they design and build LEGO® robotic devices, I have begun to see common patterns and difficulties students have with different components—using gears, motors, and sensors. Seeing these patterns, I can intervene in ways where I do not show them exactly how to do it (e.g., construct a gear train for their design), but instead present them with a simple example that demonstrates the underlying principles and let them take it from there. This allows students to become independent and not call on a teacher for the next similar component of their design. This is something the novice teachers I am training often do not see or do not do. However, the more situations the teachers begin to recognize and practice in help them develop such pattern recognition abilities.

Teaching expertise summary.

Teaching is a complex act requiring teachers to constantly call upon numerous bases of knowledge (i.e., subject matter knowledge, pedagogical knowledge, and pedagogical content knowledge). Combine this with the complex nature of engineering, which draws upon numerous fields or domains of knowledge (e.g., physics, mathematics, mechanics, economics, and chemistry), and you have a difficult challenge for teachers. Expertise in teaching engineering will look different for each individual making it important to keep in mind Sternberg and Horvath's (1995) recommendation to consider teaching expertise as an exemplar or prototype view. Future research should investigate the repertoires and routines of expert teachers and compile the many variations that emerge. Expert teachers' abilities to recognize patterns within the classroom and within engineering activities should be noted to inform what practice or development opportunities teachers will benefit most from. Lastly, these experts knowledge of students' ideas and understandings of engineering can, not only, inform future development opportunities for teachers, it can also inform curriculum development and design for middle school engineering.

Putting It All Together and Looking to the Future

Subject matter knowledge, pedagogical content knowledge, and expertise have been discussed somewhat separately up to this point. How are all these connected in teaching middle school engineering? Like engineering, teaching is a synthesis of different kinds and types of knowledge. Engineers use knowledge of math, science, history, and economics, among other fields to design and create solutions to improve the quality of life. Teachers use their subject matter, pedagogical, and pedagogical content knowledge to create environments and opportunities for students to learn. These knowledge bases do not stand alone and independent from each other. As Ma (1999) noted, a deep understanding of the subject matter can lead to developing new methods and strategies for teaching a subject—a component of pedagogical content knowledge. A teacher's pedagogical content knowledge is highly dependent upon their subject matter knowledge, yet subject matter alone does not lead to strong pedagogical content knowledge (Davis, 2003). The expertise literature in physics illustrates how subject matter experts recognize patterns, organize information, and approach problems (M. Chi, Glaser, & Rees, 1982). This may or may not make a difference in a teacher's teaching, which leads to numerous questions. How much subject matter development does a middle school engineering teacher need? What patterns will these teachers need to recognize as their students design and create solutions? What is the information and knowledge accessed in engineering design? How will engineering best be taught to prospective teachers? These questions are all opportunities for future research into examining the subject matter preparation of middle school engineering teachers.

Beyond subject matter knowledge, pedagogical content knowledge is critical in striving for expertise in teaching engineering. Teaching expertise includes knowing students (Berliner, 1986, 1994; Borko & Livingston, 1989); recognizing patterns in the classroom (Berliner, 1994); having strategies and routines for teaching (Berliner, 1994; Borko & Livingston, 1989; Leinhardt & Greeno, 1986), which can all relate back to what makes up pedagogical content knowledge (Gess-Newsome, 1999; Shulman, 1986). With sufficient subject matter knowledge (yet to be defined), the development towards expertise is strongly related to the development of pedagogical content knowledge. This leads to questions that arise when considering teaching engineering. What specific teaching strategies or routines work well in an engineering classroom? What do students know or not know that teachers will need to consider? What kinds of opportunities allow teachers to develop the ability to recognize patterns within students questions and work that allow them to shift their approach to foster understanding in their students? What does an expert middle school engineering teacher's knowledge base look like? All of which can provide new opportunities for researchers and teachers alike to inquire and discover in the emerging field of K-12 engineering education.

Implications for Teacher Professional Development

How can all of this inform future professional development designed to prepare teachers to teach engineering in their classroom? Given the dynamic and ever-evolving nature of pedagogical content knowledge (Appleton, 2003; Veal, Tippins, & Bell, 1998) and engineering (Vincenti, 1990), there will not be just one way to approach this issue, nor will just one thing work in the same fashion for each teacher. And as we saw in the expertise literature, each expert can develop their own schemata and knowledge base through their unique experiences (Chase & Simon, 1972). The best way to answer this question is to address a few possibilities that can strengthen any sort of professional development program. The use of the word *program* is quite intentional here. Engineering professional development will be best realized within a structured and long-term program. This is advised by research in teacher professional development recommending well-thought-out, extensive approaches (Deborah Loewenberg Ball & McDiarmid, 1990; Darling-Hammond, 2006; Darling-Hammond, Hammerness, Grossman, Rust, & Shulman, 2005; Fishman, Best, Foster, & Marx, 2000). A long-term program would also support pedagogical content knowledge development, which is described as a gradual and non-linear process (Appleton, 2003; Driel, Verloop, & Vos, 1998; Veal, Tippins, & Bell, 1998).

One key aspect of developing pedagogical content knowledge is described as learning from other teachers. Teachers being able to see other teachers while they teach different topics and concepts can help them develop their own strategies. This idea was exemplified in a teacher quote from an interview in a professional development workshop with middle school teachers (Hynes & dos Santos, 2007). The teacher, Rick, was commenting on one of the unexpected features of the two-week workshop. During the second week, the teachers participated in a practicum where students came for a week during the summer. Due to a lack of smaller rooms, the practicum was held in two large rooms and the teachers taught their students amongst all the other teacher-student groups. Rick commented:

> I like that in this space we not only had the opportunity to make a mistake and it would be alright, but we also got to see other people make mistakes and maybe the same mistakes we were making. I was looking at the different people and their teaching styles and saying, 'I like the way he did that there', or 'I hope I didn't do that.' Teachers never get a chance to do that. Very seldom do teachers get a chance to spend time in another teacher's classroom. So to have a big room full of kids, a big room with lots of other teachers, everyone doing the same lessons with the same expected outcomes in totally different manners or approaches, maybe similar approaches, but we are all doing the same lessons, we may be doing it differently, and seeing what works for whom, and then predicting 'Oh, that will never work' and then watching it work for that person. And then recognizing that it worked for her and it might not work for me. We don't get a chance to do that. I have been teaching for 30 years I've never gotten a chance to do that. I certainly would have welcomed that when I was 23. (Hynes & Santos, in press, p. 16)

This highlights the extraordinary opportunity it was for this teacher to observe and learn from other experienced teachers.

Another apparently important source for developing pedagogical content knowledge is working with and interacting with students. In terms of professional development, a practicum or sessions following classroom teaching would be a likely way to incorporate teachers interacting with students. This is a common practice in professional development, and I would recommend that it be incorporated with other long-term strategies to ensure that it provides full benefit. This practice not only allows the teachers to test out what they have learned, but it gives them instant feedback and allows them to see what they need to work on or develop to further assist them in fostering a deepening in their students' understanding. The teachers may also require time to self-reflect or reflect with others to capture what happened during the course of a lesson or interaction.

The last strategy I will mention is designing educational materials that will promote a teacher's subject matter and pedagogical content knowledge development by providing examples, analogies, and possible students' misconceptions for very specific topics and concepts within the subject area. These materials can be very beneficial to teachers in the absence of other resources (Davis & Krajcik, 2005). A teacher may not have adequate experience with a certain toolset or curriculum to deliver a lesson with expertise. However, materials that prepare them for potential challenges or issues in the classroom may guide them through the lesson.

Conclusion

More and more engineering is playing a valuable role in our society and, as such, many believe it should be incorporated into the K-12 classroom. Before it makes it to the classroom, it has to make its way into a teacher's knowledge base such that they are prepared to teach it. We have looked at the teacher's knowledge base and concluded that engineering subject matter and engineering pedagogical content knowledge are the two main knowledge bases that would be the most important to focus on in developing engineering teachers. From a deeper look into subject matter knowledge, it is clear that a deep understanding of engineering would likely lead to stronger teaching. If a teacher has a deep understanding of the engineering principles at work, they will likely be better able to simplify some of the complexities of engineering into simpler forms their students will understand. Thus, we will want to recognize what courses or topics of study teachers will benefit from the most. Subject matter knowledge is also linked to pedagogical content knowledge. Limited subject matter knowledge does not allow teachers to develop pedagogical content knowledge, which includes strong strategies, examples, or contexts for their students. Beyond these ties, pedagogical content knowledge, itself, is an extensive body of knowledge that teachers develop over time and within their practice. It appears to be a critical body of knowledge for engineering, as engineering is often taught with open-ended design projects that require teachers to use real-world contexts and examples. After reviewing literature of these knowledge bases, the review of the literature in the areas of expertise for content areas—physics and chess—as well as in teaching strengthened and supported many of the conclusions about the need for depth in subject matter knowledge and the complexities of pedagogical content knowledge. The research reviewed also provided a framework through which to look at the development of engineering teachers as they progress from novices in engineering and teaching engineering to expert engineering teachers. Namely, researchers will want to look at how expert teachers make sense of what they are experiencing in the classroom and recognize patterns of students questions and actions that they use to change the course of action during the lesson. Research will also want to look at the routines of practice within the classroom that experts develop. This repertoire of routines can be used as frameworks for future engineering lessons and curricula. New strategies to foster student understanding for the many areas of content within engineering will also emerge as researchers learn from these developing teachers.

This review answered very few questions in what will qualify a middle school engineering teacher or how to prepare one. Instead, I developed new questions and, hopefully, some guidance or frameworks that can assist the future research in this field. Results from which may expand and improve the opportunities for students to engineer within the world around them.

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