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Middle Grades Teachers' Understanding And Teaching Of The Central Ideas Of The Engineering Design Process

MORGAN HYNES
Tufts University
Boston, MA

ABSTRACT

The research reported on in this paper addresses the problem of preparing Massachusetts middle school mathematics, science, and computer teachers to teach engineering. The results presented here are part of a larger dissertation study investigating six urban public school teachers and their subject matter and pedagogical content knowledge teachers know and develop as they taught an engineering unit. The results discussed in this paper focused on the teachers' instruction and knowledge of the central aspects of the engineering design process (EDP)—the purpose of the EDP, that the EDP is a cyclical, iterative process, and that the EDP fosters communication. The analysis of the videotaped classroom observation data revealed that the teachers as a group covered the central ideas regarding *1. Purpose of the EDP* and *2. EDP as a cyclical process* quite well. Every teacher touched upon at least one of the sub-ideas for these two central ideas. The teachers did not cover *3. EDP for fostering communication* well. Only Frieda and Monica conveyed anything regarding this idea to their students. This paper explores each central idea and the teachers' understandings of them as expressed through their explanations in the classroom observations and follow-up interviews.

Keywords: engineering education, engineering design process, teacher knowledge, teacher professional development

INTRODUCTION

Learning about engineering within science curriculum has gained traction throughout the U.S. A recent draft of National Science standards places engineering alongside the other science disciplines (i.e., physics, biology, and chemistry) as a discipline to be taught within the domain of science (Board on Science Education, 2010). Massachusetts state curriculum frameworks have included engineering within their Science & Technology/Engineering frameworks since 2001, which outline engineering concepts and topics that should be addressed in grades 5–12 (Massachusetts DOE, 2001). As government, industry, and education organizations continue to call for the improvement of science, technology, engineering, and mathematics (STEM) teaching and learning in our K-12 classrooms, engineering is a relatively new idea for the K-12 classroom has limited history in the classroom and as such few teachers prepared to teach it. The research study discussed in this paper was designed to better understand the issues and challenges associated with preparing middle grades teachers to teach engineering leading to the driving research question:

> *What subject matter knowledge AND pedagogical content knowledge do middle grades teachers use and develop as they teach an engineering unit focused on the engineering design process*?

This research question, which represents the focus of a dissertation study (Hynes, 2009) discussed only in part in this paper, was born out of the idea that we cannot expect to have engineering teachers who have the same domain-specific preparation as those who teach mathematics or science. Generally, middle grades teachers who teach mathematics or science have either majored in or taken a significant number of courses in the subject. In the short-term, it is unlikely to have middle grades engineering teachers who have majored in engineering or even taken a college-level engineering course since it has not, traditionally, been a route for those who attain a degree in engineering. Thus, we need to learn how to prepare teachers to teach engineering. Since engineering is often thought of as the application of science and mathematics principles to practical ends, it may make the most sense to work with science and mathematics teachers and prepare them to teach introductory engineering concepts. However, we do need to understand: *What do these teachers need to know, and how do they use this knowledge in the classroom?*

The study presented in this paper followed six middle grades teachers as they taught the same engineering curriculum. The analysis included in this paper focuses on these teachers' understandings and explanations of some of the ideas central to the engineering design process (EDP), which is a central theme to engineering in the K-12 classroom as it translates well through the grades and is thought of as a strand that cuts across many disciplines of engineering (Bucciarelli, 1994; ITEA, 2002). The data in the form of classroom observations and teacher interviews provide some interesting evidence for how these teachers conveyed the *purpose of the EDP,* the idea of the *EDP as a process,* and the idea that the *EDP fosters communication* among stakeholders.

TEACHER KNOWLEDGE

A teacher's knowledge base for teaching is a complex web connecting a diverse set of domain specific (e.g., mathematics, science, and engineering), cultural or contextual, pedagogical, psychological (e.g., students' abilities, emotions, and behaviors), technological, and various other types of practices and knowledge that teachers call upon from moment to moment. Shulman (1986, 1987) sparked the conversation to consider the vast and varied knowledge teachers must use and develop in the ongoing education reform environment. He drew attention to and categorized teachers' knowledge beyond the more traditional notion that teachers simply needed to know a domain's content area well to teach it, introducing the construct of pedagogical content knowledge (PCK)—the specific knowledge for teaching specific subject matter. Ball (1988, 1993, 2000; Ball, Thames, & Phelps, 2008) has painted an equally deep and complex picture of how a teacher must understand and know subject matter, specifically mathematics, beyond simply how to apply and use mathematics to include knowledge of the various ways students will come to construct mathematical knowledge, of the "horizon" knowledge that they are building toward, and how to identify the mathematical ideas and reasoning in student work (Ball, 1993; Ball, Thames, & Phelps, 2008).

In mathematics, Ma (1999) showed us that a depth of subject matter knowledge was often more important than a breadth of knowledge. It was more important that teachers had a deep understanding of the topics their students were learning (e.g., multi-digit multiplication) than knowledge of calculus or differential equations when it came to teaching multi-digit multiplication in the classroom. Similarly in science, Davis (2003) demonstrated how a teacher could have strong knowledge of a topic (in this case the properties and characteristics of light) yet be flawed in her instruction as she makes marginal connections between scientific ideas and real-world examples her students might relate to. Hill, Rowan, and Ball (2005) have also provided strong evidence that a teacher's mathematical knowledge was significantly related to their students' mathematical achievement. They assessed the teachers not on traditional mathematical knowledge (e.g., standardized tests or college coursework) but on the kind of knowledge teachers would use in the classroom (e.g., the computational methods students might use or determining the validity of student work and reasoning). Ideally, teachers teaching engineering would have a deep understanding of engineering and the mathematics and science ideas and practices that will be associated with the engineering activities at the specific grade level. However, I contend that teachers can and will develop the kind of knowledge they need to teach engineering through focused professional development opportunities and classroom practice. This contention is based on the idea that teachers will bring intuitive knowledge—knowledge not formally taught in school but developed through one's intuition or in the field of practice—as defined by Lampert (1986), as well as personal experiences with designing and building, and build knowledge alongside their students (Doerr & English, 2006) as they develop engineering pedagogical content knowledge.

THEORETICAL FRAMEWORK CENTRAL IDEAS OF THE ENGINEERING DESIGN PROCESS

As teachers integrate the EDP into their classrooms, they should understand some central ideas related to the larger purpose and context for why engineers use the EDP. The engineering curriculum and associated professional development the teachers used and participated in for this project used the Massachusetts Department of Education's (DOE) model of the EDP (see Figure 1). This model depicts a step-wise process; however, the professional development team (that included the author) did not want teachers to think of it as a prescriptive process to be memorized, but rather a process through which engineers engage in a number of common practices as they develop solutions. The following central ideas of the EDP are broken into the categories: (1) purpose of the EDP, (2) EDP as a process, and (3) EDP for communication. Within these categories there are key understandings or ideas the team wanted teachers to know and convey to their students.

Purpose Of EDP

The EDP is a tool that supports engineers in thinking clearly, making good decisions, and ensures nothing important is overlooked leading, ultimately, to high quality solutions and products (Dym & Little, 2004; Ullman, 2003). (b) Since "design problems are ill-defined" or sometimes "wicked"

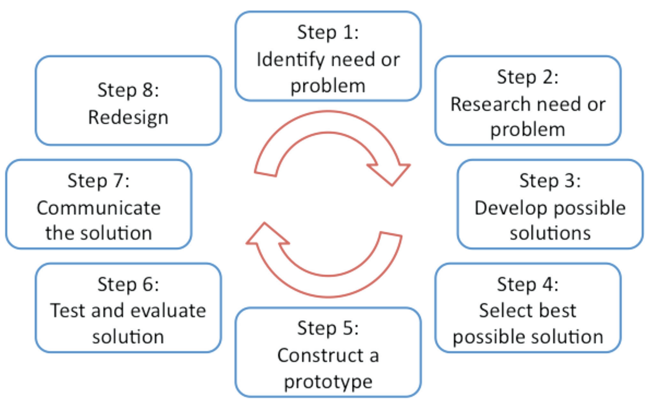

Figure 1. Massachusetts DOE (2001) model of the Engineering Design Process.

(Buchanan, 1995; Simon, 1996) and "have a multitude of satisfactory solutions" (Ullman, 2003, p. 15) the EDP helps guide engineers through a process of considering multiple ways of framing problems through information gathering (Bursic & Atman, 1997), considering multiple solutions as they consider the myriad constraints and requirements posed by the problem. (c) Considering that there are so many possible solutions (Atman et al., 2007), it is safe to say there is unlikely a perfect solution to any particular engineering problem. Since no solution is perfect, engineers can always be improving or optimizing existing solutions.

EDP as a Process

The systematic nature of the EDP takes an engineer through a series of checks to ensure they do not miss critical details (Ullman, 2003). (b) The EDP is also iterative, meaning that after you have created and tested a possible solution, you may find that there are improvements that can be made, thus starting the process over again. (c) However, this does not mean that you have to go step-by-step without ever skipping back a few steps or ahead a few (Adams & Atman, 2000; Atman, Chimka, Bursic, & Nachtmann, 1999). For example, you may conduct some research then brainstorm possible solutions and then realize that you must go back and conduct more research because new issues emerged during brainstorming. An engineer may iterate between these two steps a number of times before moving on and may revisit them later on in the development of the solution.

EDP as communication

Most engineering design problems follow a human-center or user-centered design model (Norman, 2002) where there is an engineer or designer designing with some end-user or client in mind (Dym & Little, 2004). The EDP takes the engineer through various stages where they communicate with the client to ensure the solution is meeting their needs, and with other members of the design team or company to ensure that the solution meets the needs of the company (e.g., financial, marketing needs) (Lawson, 1997; Ullman, 2003; Visser, 2006). From the Massachusetts DOE model this communication may commonly take place in steps 1, 2, and 7, when the engineer is given a problem or need from a client and then researches that need or problem by asking the client questions about the kinds of requirements they desire. (b) In step 7 the engineer or designer communicates the current solution to get feedback on potential redesigns (Dym & Little, 2004). The communication with users and team members can take many forms. Engineering drawings, simulations, or other representations may be used in pre-prototype stages or to communicated ideas to and get feedback from potential manufacturers in distant locations (Cross & Roozenburg, 1993; Simon, 1996; Vincenti, 1990; Visser, 2006). Physical prototypes can be used to have clients start testing out the product and can be a centerpiece for conversation.

METHODS AND STUDY DESIGN

The dissertation study from which this data comes followed a case study analysis methodology (Yin, 2003) where the principal investigator followed six middle grades teachers as they taught the same engineering unit. The goal of the study reported on in this paper was to understand the knowledge teachers used *in* the classroom. Thus, it was critical that data be collected in the classroom. The research team videotaped classroom teaching, interviewed the teachers, and presented the teachers with hands-on, think-aloud interview tasks (van Someren, Barnard, & Sandberg, 1994).

The Teachers

Six middle-grades teachers made up the sample for the study. These teachers all taught for schools in the Boston Public School (BPS) system. Teaching in Boston, these teachers were situated in schools that are racially, ethnically, and culturally diverse. The demographics of the students in the participating teachers' schools is shown in in Table 1 below highlighting the race/ethnicity of the students and free or reduced lunch status. (Boston Public Schools, 2011).

The teachers had participated in a professional development workshop that prepared them to teach the engineering curriculum that will be outlined in the next section. The teachers were a mix of fifth, sixth, seventh, and eighth grade teachers that taught a range of subjects including general fifth grade curriculum, mathematics, science, and computers. See Table 2 below for the background of each teacher. All teacher names are pseudonyms.

Enrollment Data	School 1 (%)	School 2 (%)	School 3 (%)	School 4 (%)
African American	25.7	5.1	56.8	17.4
Asian	1.1	.4	5.9	1.7
Hispanic	69.8	85.1	29.9	23.0
White	1.6	8.0	6.1	56.2
Other	1.8	1.4	1.3	1.7
Free Lunch	87.0	79.6	75.6	57.4
Reduced Lunch	5.6	8.4	9.8	6.0
Teachers	Frieda, Maria, Victor	Sonya	Monica	Scott

Table 1: Demographics of students at participating teachers' schools.

Teacher	Years teaching	Grade(s) taught	Subject(s) taught	Bachelor's degree in	Master's degree in
Frieda	0	7, 8	Science	Biology	Teaching
Monica	3	6	Mathematics	Finance	None
Scott	3	7	Mathematics & Science	Humanities	Teaching mathematics*
Victor	5	5	General	Business	Teaching
Sonya	16	K-5	Computers	Cultural anthropology	Teaching computers
Maria	17	5	General	Mathematics & physics	Bilingual education

Table 2: Teacher profiles.

* Currently pursuing master's degree

The Engineering and Design Curriculum

The teachers all used the same engineering-design based LEGO robotics curriculum, but they were not required to teach it "by the book." The teachers were told they could modify, add, or remove lessons from the curriculum as they saw fit. The author and a team from Northeastern University and TechBoston (a group within the Boston Public Schools [BPS]) created the curriculum, which is freely downloadable at http://www.legoengineering.com. The curriculum was designed to address Massachusetts's curriculum frameworks for Engineering/Technology. The curriculum focused on addressing the standards for engineering design and assistive technologies. Students used the engineering design process to solve small design challenges where they developed knowledge and skills in identifying problems, developing, testing, and redesigning solutions using the LEGO robotics toolset. Table 3 provides a brief outline of the curriculum.

The Teacher Professional Development Workshop

The professional development workshops the teachers participated in was designed to introduce them to teaching the aforementioned LEGO robotics curriculum. There were two kinds of workshops the teachers participated in: (1) a two-week summer workshop that included a practicum (Frieda, Sonya, Maria, and Scott); and (2) a 5-day school year workshop with no practicum (Monica and Victor). The first week of the two-week workshop was identical to the 5-day school year workshop. The two-week workshop was led by the author and co-led by another project member who also led the 5-day school year workshop. During the workshops, the teachers went through each of the lessons just as their students would, but were then given complementary lessons to investigate the concepts (i.e, the physics behind gears or the computer science of LEGO programming) more

Challenge (estimated time)	Description
Spatula design (1–2 hours)	Students build a LEGO spatula that must be long and strong. The students test the spatulas, then redesign the spatulas, and retest them. The class then discusses the Engineering Design Process.
Wheelchair design (1 hour)	Students build a LEGO wheelchair that must be able to hold a bottle of water, be at least 8 inches tall, be able to roll freely, and survive a drop test. The teacher begins the challenge with a discussion about constraints and design.
Design selection (1 hour)	This is a multi-part challenge. The discussion revolves around selection and design criteria and how they play a role in the EDP. First, the students have to select the "best" LEGO wheelchair drive train based on a number of criteria.
Design selection continued (1 hour)	The discussion for the second part of the challenge revolves around using orthographic drawings, learning how gears work, and constructing the model. The students use a set of orthographic drawings to construct the model they chose.
Design selection continued (1 hour)	Finally, the students, with the constructed models, test and evaluate the models. The teacher then has the students discuss and compare all the different models that were tested.
Programming (1–2 hours)	The teacher introduces the students to the concept of computer programming and, specifically, the ROBOLAB programming language. The students use the models they built in the previous challenge to complete simple programming challenges.
Programming with sensors (1–2 hours)	The teacher begins this challenge discussing how sensors work. The teacher relates sensors to both the human senses and to the LEGO sensors. Students are then given programming challenges that incorporate the LEGO light and touch sensors.
Assistive device final project (4–8 hours)	The final design challenge asks the students to create an assistive device using the LEGO toolset with a minimum of 1 sensor, 1 motor, and the RCX brick. The students work through the entire EDP as they create their projects.

Table 3: Robotics curriculum outline.

deeply. Throughout the workshops the instructors attempted to model best practices for teaching engineering and teaching using the LEGO robotics toolset. More details regarding the professional development workshop can be found in a prior publication of the work [see (Hynes & dos Santos, 2007)].

Data Collection and Analysis

The author collected data in the form of: (1) semi-structured interviews, (2) videotaped classroom observations, (3) hands-on think-aloud interview tasks, and (4) student projects. Each teacher participated in an interview before and after teaching the curriculum. Some teachers participated in an interview during the unit. Within the interviews, the teachers also engaged in hands-on, think-aloud tasks to elicit their ideas about engineering. These methods of data collection allowed the teachers to verbalize what they did and experienced, and allowed the author to ask questions about what the teachers had done in the classroom (Appleton, 2003; Dawkins, Dickerson, & Butler, 2003; Veal, Tippins, & Bell, 1998). The author also videotaped a number of the teachers' classroom sessions to capture evidence of their knowledge of the central ideas of the EDP.

Using these data collection tools allowed for triangulation to confirm and strengthen the data analysis. Classroom observations, alone, were effective in providing data on what teachers did and said in the classroom, but were only able to elicit what can be observed. Thus, they do not capture what the teacher is thinking or doing in their mind. Follow-up interviews with the teachers provided data regarding what the teacher was thinking or the knowledge they elicited during the observed incidents. This paper focuses on analysis of data from both interviews and classroom observations.

The author used Miles and Huberman's (1994) qualitative data analysis approach to analyze the interview, task, observation, and student project data. The approach incorporates different types of data into displays and matrices to help reduce and organize data for analysis. The reduced data allows the author to note patterns and themes, cluster data, make comparisons, and note relationships. The development of new coding schemes further organizes and reduces the data into conceptually ordered matrices and charts, which are analyzed further. Both within-case analyses for each teacher and cross-case analysis among the teachers were considered throughout the analysis. It is important to note that the author participated in all aspects of curriculum development, teacher professional development, data collection, and data analysis. The author did collaborate with others in all aspects of these activities; however, it does present a validity threat to the design of the study. That being said, the data is presented in a case study approach where you can, hopefully, judge for yourself whether the interpretation of the data fits the data.

TEACHERS' KNOWLEDGE OF THE CENTRAL IDEAS OF THE EDP

The eight steps of the EDP, on their own, do not capture the full intent of the EDP. Findings regarding teachers' knowledge of the steps of the EDP are presented in previously published work (Hynes, 2010). Thus, teachers should have an understanding of some of the central ideas of the EDP as previously discussed. For the purposes of this study, I was most interested in the knowledge the teachers used in the classroom. Thus, their knowledge of these ideas was primarily assessed by whether or not they presented the idea to their students in the classroom. The follow-up interviews also allowed the teachers to express this knowledge, which was considered for the analysis since the author did not observe all classroom sessions. Table 4 portrays the central ideas that the teachers were either observed covering in their class (C) or in a follow-up interview (I). The data analyzed here comes from the observation of Lesson 0 and a final project lesson. Lesson 0 is the first lesson of the project, and the lesson where the teachers introduced the engineering design process to their students. The final project lesson was observing the teachers and students as they were working on their final projects. Since classroom sessions were of varying lengths for the teachers, the observations were done such that at least one and a half hours of observation were conducted for each classroom, which for some teachers spanned two sessions. All teachers were also observed throughout the unit during other lessons, but there is no data from those observations presented in this paper.

The totals reveal that the teachers covered the majority of the central ideas regarding *1. Purpose of the EDP* and *2. EDP as a cyclical process*. Every teacher touched upon at least one of the sub-ideas for these two central ideas. The teachers did not cover *3. EDP for fostering communication* well. Note that the teachers may have covered these ideas in other lessons that were not observed. Only Frieda and Monica were observed conveying anything regarding this idea to their students. The following discussion explores each central idea and the teachers' understandings of them as expressed through their explanations in the classroom observations and follow-up interviews.

EDP central ideas	Frieda	Maria	Monica	Scott	Sonya	Victor	Totals
1. Purpose of EDP							
a. Ensure a quality product/solution*	I	C	C	C		C	5
b. Consider multiple solutions/ideas*	I	C			C	C	4
c. Make improvements*	C	C	C	C	C	C	5
2. EDP as a cyclical process							
a. An iterative cycle*	I	C	C	C		C	5
b. Web-like can jump from step to step	C	C	C		I	C	5
c. Systematic process*	C	C	C	I	I	C	6
3. EDP for fostering communication							
a. Represent solutions to others	C						1
b. Receive feedback from team members/users*	C		C				2
Totals	8	6	5	4	4	6	

Note: The cells indicate whether the teacher covered an idea in the classroom (C), in an interview (I), or not at all (blank). The star (*) indicates ideas that were included in the curriculum manual.

Table 4: Central ideas of the EDP covered by the teachers.

Teachers' Knowledge of the Purpose of the Engineering Design Process

Engineers learn and apply the EDP because it serves a purpose. Ideally, teachers and students should understand why engineers use the EDP and, thus, why they would want make use of it in their own engineering design projects. All the teachers in this study discussed with their students at least one of the key purposes of the EDP, and most of the teachers (5/6) hit on two of the three key purposes of the EDP with their students.

In the following dialogue, Monica is discussing the importance of a prototype with her students:

Monica: Why would you want to create a prototype first?

Colin: To test our idea.

Monica: We have to test it. Why do we have to test it?

With this question, Monica is hinting that there is some reason or purpose behind creating a prototype and then testing the prototype—two key steps of the EDP. The conversation continues:

Colin: Who knows what measures, what measures it can… what can happen.

Monica: Who knows what can happen? Ok. Something could not work. Do we want to make sure it works in a prototype form first before we try and sell it to somebody or do we want to wait for the final product and then make sure it works?

Here Monica has introduced some reasoning for having and testing a prototype, namely, making sure it works before selling a final version of the product implying that there would be some negative impact to selling an untested product. Her student's response below, which may just be her misunderstanding the question, provides Monica an opportunity to emphasize her point:

Sasha: Wait until the final product.

Monica: If we wait for the final product and it doesn't work, then what happens?

Sasha: It is messed up.

Monica: What about all the money you put into it? Wouldn't you rather find out when you build the prototype that it doesn't work, that way you can start all over again?

Students: Yeah. (*Lesson 0 observation*)

In response to her student, Monica has highlighted that within steps of the EDP you 1a. *ensure a quality product* in terms of financial consequences, which is a very real part of engineering new products. In her last point, she also hints to the idea that you can iterate on the idea or 1c. *make improvements* if you find out your prototype doesn't work. Monica does this without the curriculum manual in front of her, and, I presume, understands these ideas central to the EDP.

Sonya related her 5th grade students' process of coming up with ideas to 1b. C*onsider multiple solutions/ideas*:

Sonya: Describe and refine possible solutions … did you draw an idea? [*Students nod*] Did you use the ideas? [*Students nod*] Yes. Did you change the ideas? [*Students nod*] Yes. (*Lesson 0 observation*)

Sonya may also be hinting toward the big idea 1c. *Make improvements* when she asks the students if they changed ideas in reference to the refining of possible solutions. It is less clear in this example as compared to the previous example from Monica whether or not Sonya explicitly understands these big ideas as the central purposes of the EDP as she does not expand further on these questions she asks her students, but it does provide some evidence that she believes it is important to highlight these ideas with the students.

Maria elicited the following from her student when asking the class to explain what the EDP is all about:

Sharea: It's [the EDP] a list to improve the quality of a product. (*Lesson 0 observation*)

Sharea's response addressed ideas 1a. *Ensure quality product* and 1c. *Make improvements*. Maria was happy with this response, which also highlights the point that the students will be bringing their own understanding and reasoning to the proverbial table and that these central ideas can be elicited from them.

These cases from Monica, Sonya, and Maria demonstrate that these teachers, with limited engineering experience, are understanding and conveying the core purposes of the EDP. Of course, there is room for improvement and some things could be made more explicit; however, even small references to the core purposes of the EDP throughout engineering activities are what important as teachers introduce engineering to young students.

Teachers' Knowledge of the EDP as a Cyclical Process

Teachers and students should also understand the cyclical nature of the EDP. It is not necessarily a process you go through once to end up with a finished solution. Engineers start the process over again if they identify areas that need redesign. Engineers also may jump from one step to another out of order or even backwards. For example, while constructing a prototype (step 5), an engineer may go back to researching the need or the problem (step 2) again to ensure the prototype addresses some new constraint they had not anticipated. Three teachers addressed all three points of idea 2. *EDP as a cyclical process* with their students, and the other three either covered two of the three points with their students or revealed their own knowledge of the idea in an interview. Victor's discussion of the EDP with his students could serve as an exemplar for underlining idea 2a. *An iterative cycle*:

Victor: If you look at the flow of this, what's the flow? How does this … how does this design process set up I guess? Reggie, look at your paper, how is this whole thing set up?

Reggie: It's a system really…

Victor: It's a system.

Reggie: Because it's…

Sheila: An oval.

Calvin: They would research about it and then go on and on and figure out what to do with this problem and try and solve it.

Victor: Ok. Sheila?

Sheila: It's an oval.

Victor: It's an oval. Why do you think it's an oval or a circle or some form of cycle? Why do you think … I know you guys just came back from lunch, you did all this testing, you had a lot of fun doing it, you made some nice improvements to your original design, but believe it or not you did this today. In class without even realizing that you did it … and you went back and you identified the need again or the problem. I needed to add connectors to my handle. I needed to make, as Calvin said, I need to add some bricks to the bottom of the plate of my spatula to make it stronger. You did this today. Did you realize you did this? (*Lesson 0 observation*)

Victor not only addressed the idea that the EDP is iterative by describing that the students can go back and identify a new need or problem with their design, but also connected it to their own experience of building the spatula. By connecting the ideas of the EDP back to the students' experience, Victor is displaying PCK where his knowledge of what students were doing as related to the EDP comes through in this interaction.

Frieda and Victor both addressed idea 2b. *Web-like* with similar simple, yet accurate approaches:

Frieda: Just like the scientific method sometimes they are out of order, but you still cover just about every step. (*Lesson 0 observation*)

Here Frieda is also displaying PCK by referring to the scientific method, which is something she knows her students have practice with.

Victor: … I mean you might not go through all these steps, but you might jump around and that's what engineers do. (*Lesson 0 observation*)

Victor highlights that engineers do not always go through all the steps and may jump around illustrating that he does understand that the process is not prescriptive and that he is thinking about the practice of real engineers in his conversations with his students.

Maria highlighted the ideas 2c. *Systematic process* and 2b. *Web-like* in the following interaction:

Maria: Is the EDP systematic and step-by-step?

Students: Yes.

Maria: But can you jump around too. Like go from step 6 to step 4?

Students: Yes. (*Lesson 0 observation*)

Maria's two questions appear to contradict each other; however, she demonstrated that she knew that the systematic nature of the EDP was important, and did not rule out jumping around within the EDP.

All the teachers demonstrated that they understood the cyclical nature of the EDP through their explanations. However, teachers may benefit from having more explicit cues in the curriculum for when to talk about this idea. The curriculum could also include more opportunities for the teachers and students to discuss how they worked through the process: whether it was jumping from step to step in the EDP or iterating through the EDP multiple times in a given lesson. Frieda provided excellent examples of how redesign can be thought of as both continuous iteration within one design cycle and as something that would be done as a future redesign of a product (e.g., version 2.0).

> Frieda: At the same when you're redesigning I want you to also, to also think about why you redesign and what didn't work. (Lesson 0 observation)

In this first example, Frieda asked her students to reflect on why they were redesigning, and implied that it related to what did not work in their previous iteration. In the second excerpt, below, Frieda described to her students how the redesign step of the EDP referred to the future redesign of a product or solution that could be improved upon (multiple versions):

> Frieda: Step 8 the redesign. So the redesign is just after you come up with whatever it is that you want to design. For my sixth graders it was the laser pen. After they created it, they saw how far it could go with their prototype so they would say it was a nice pen, but next year I want to add a few more things to it. I want to add maybe, I don't know, a feature with a clock in it or something so you could see what time it was while you're pointing at things… something like that. Or for my house that I constructed the prototype maybe I want to add a garage to it, so I'm redesigning it, all right. I'm redesigning it. Redesign. Even when you did your projects for the science fair, some people tested theirs out and I said what would you do differently because some people they tested theirs and things weren't working. What would you do differently? All right, that's step 8. So that's the engineering design process. (Lesson 0 observation)

From these two examples, Frieda hinted at two interpretations of redesign, which relates back to the cyclical nature of the EDP. The following excerpt from an interview with Frieda, illustrates that she did indeed understand the two interpretations of redesign and that this was related to how she frames her "bigger picture" understanding of the EDP.

> Frieda: But the redesign I put last [in her model of the EDP]… I guess because it is last thing… sometimes… I mean I guess it is one of those that could go out here throughout the whole thing because you are constantly redesigning. I think it could go all the way back to need sometimes… you may say I don't want to do that. So the redesign I have as last. The redesign is intricate in terms of what to look forward to in the future if you missed a few things. If people want to give feedback or ask questions that may make you think of something else that will make you think of something to add to the redesign. So that's why I put it after presentation because sometimes… well it can go after presentation because sometimes after you present things people come back

and may tell you their suggestions or tell you things that may help or may hurt and you can always go back and redesign. (Final interview)

Frieda appears to have a firm grasp on the idea of redesigning as part of the EDP and how it relates to its iterative nature. This is the type of understanding I believe we should strive for as we prepare teachers to integrate engineering and the EDP into their classrooms. As Frieda presented to her students, there are very clear real-world examples that explicate these ideas of redesign and design iteration.

Teachers' Knowledge of the EDP for Fostering Communication

Frieda and Monica were the only teachers that were observed alluding to the idea 3. *EDP for fostering communication*. This should not be considered as a failure of the other teachers, but as an acknowledgement to Frieda and Monica for addressing an idea that was not emphasized explicitly in the curriculum or curriculum materials. It also serves as evidence for the need for professional development and curriculum that makes a stronger point for communication aspects of the EDP. The teachers in this study had limited exposure to representing solutions in methods other than LEGO prototypes and communicating with people outside the professional development workshop as they learned how to teach the curriculum. Thus, it might be unreasonable to expect the teachers to fully understand the arduous process of submitting drawings and specifications to clients and receiving feedback from them as engineers do.

In the analysis of teachers' explanations of step 7 (communicate the solution) of the EDP, some teachers forgot or almost forgot to mention step 7 highlighting that communication was likely not something these teachers associated with the EDP. For example in an interview, Scott explained that step 7 was a step he would have left out:

Scott: I would… I normally would have gone to here (points to EDP handout from step 6 to step 1 to close the cycle). To me I wouldn't have thought about communication until you already had something done. And then you communicate to whomever you communicate to. But I remember that being part of the thing. *(Final interview)*

Scott demonstrated that communicating the solution was not part of his personal conception of the EDP and that is was more for final presentations. Other teachers also skipped from step 6 to step 8 forgetting to include step 7 before looking back and realizing their mistake:

Frieda: The last thing… well in between that I have presentation because you probably want to present it. (*Final interview*)

Monica also seemed unsure of what came after the testing and evaluating step of the EDP as she hesitated and checked her manual while discussing the next step with her students:

Monica: Ok. You definitely want to find the problem. What do you want to do eventually?

Colin: Figure out what's going on. □

Monica: Give me a moment I have to look and make sure I am doing this right (looks at EDP handout in her manual). Yeah, ok. So when you find out what is going on what do you want to do with each other? Suppose you know what is going on and he doesn't … what do you need to do? □ (*Final project lesson observation*)

Victor pointed to another issue that may have prevented the teachers from highlighting the step successfully:

Principal investigator: What do you struggle with regarding communicating the solution? □

Victor: I have it up here (points to head) but I just can't get it out sometimes. □

Principal investigator: So having the correct terminology or words? □

Victor: The correct terminology or complete understanding of it… I don't want to say something that is completely false when it came to the whole gear ratio… you had mentioned torque the last time we were here… I don't want to touch that if I'm not too sure. □ (*Interview #2*)

Even if teachers understood when and where communication should be included in the EDP, as Victor points out, they may not have the knowledge or terminology to accurately communicate what is going on with the solution. Victor even attempted to make this clear to his students:

Victor: What we really need to do is start thinking about, again, what worked well, what didn't. How can you communicate our solutions? And that's really what I think we need to look at… how are we communicating. [Circles question on board]. Instead of saying I put the thing on the piece and it went that way. My thing won't go straight. Well, what did you do to make your thing go straight. What is the thing? We've talked about terminology, being specific. What is this red piece (LEGO beam) called? (*Final project lesson observation*)

While in this excerpt Victor does mention the idea of communicating as a part of engineering, he does not explicate the purpose of communicating just that we need to communicate more clearly with each other. This is certainly a positive thing for students to do and practice, but I did not categorize this as an explanation for the importance of representing solutions to others or for getting feedback from potential users or team members. That is not to say that the students might not use this feedback from Victor to do that, but I do not believe we have strong evidence that Victor is thinking of the EDP as communication in this instance.

Frieda and Monica were also the only teachers that demonstrated through their teaching an understanding of the idea that the EDP fosters communication as demonstrated in other analysis in the dissertation. Monica connected step 7 to what her students did and then extended beyond this by giving an example of how the engineers, who designed a chair, communicated the solution:

Monica: Step 7 communicate the solution. Did we communicate?

Students: Yeah.

Monica: We talked about the different solutions and maybe what was wrong with it and what was good about it?

Students: Yes (Lesson 0 observation)

Hannah: Communicate the solution

Monica: Communicate the solution. When they created this chair they communicated they had to communicate… they had to advertise about it maybe, right. Communicate with different departments. Find out if it was going to work, right?

Students: Yeah. (*Lesson 0 observation*)

In the second interaction, Monica suggested that engineers would have communicated the solution to the public and to different departments within the company. Given that students are not situated in a company, the example Monica gave provided the connection from what the students did to what happens in the real world with the EDP. Frieda also connected communication to real-world examples. She built upon the examples of building a model of a house and her sixth-grade students' laser pen project:

Frieda: Step 7 is communicate the solution. So, communicating the solution can be a few different things. It can be either me when I am thinking about my house and talking about my house. Me communicating to the people who are going to build it exactly what I want or if for my sixth graders who came up with the pen for them they want to sell that pen because they think theirs is better than what is out there. They're communicating to the public, like hey you want a better laser pen, buy this one, alright. So that's what communicating the solution communicating the solution that's step 7. (*Lesson 0 observation*)

Both Monica and Frieda provided more than one example of the kinds of people engineers communicate with about their solutions. This is important, as communication should not merely be considered a simple final presentation of your product, which is often a problematic presentation of this stage of the process (see Figure 1). Engineers constantly engage in dialog with departments within the company, external contractors or manufacturers, and potential users. In a classroom setting, it would be easy to simply depict communication as a final presentation or report to the class regarding the features of the solution. The fact that they struggled with communication aspects of the EDP may be, in part, due to the lack of an authentic opportunity for the students to be communicating with clients, manufacturers, or others within the confines of the classroom for this curriculum. Future revisions of the engineering unit should include practices where students communicate within their groups and with the entire class beyond just a final presentation. Kolodner and Nagel (1999) presented such practices in their description of design discussion areas, which they incorporated into their project-based learning curricula. If possible, models such as EPICS (Engineering Projects In Community Service) (Coyle, Jamieson, & Oakes, 2006) could be implemented where student teams work on real projects that serve the community where they communicate directly with community members as they define the problem and share their results.

Summary of Teachers' Knowledge of the Central Ideas of the EDP

The teachers demonstrated strong knowledge of the central ideas associated with the purpose of the EDP and the EDP as a cyclical process. They appeared to be weaker in their knowledge of the EDP as a tool for fostering communication. This may be a result of the curriculum materials and teacher workshops not emphasizing this idea as well as it did the other two ideas. The teachers may have viewed the purpose of the EDP as a critical piece for themselves to understand and convey to their students. Understanding the purpose of something is related to, "why do we need to know this?" which often has to be answered before moving on with learning. Thus, the teachers acquired this knowledge out of need and presented it to their students to create a context for why engineers use the EDP. The fact that the EDP is drawn as a cycle (see Figure 1) likely makes the idea of the EDP as a cyclical process salient for the teachers. In order to ensure that teachers understand and teach the idea of the EDP as a tool for fostering communication, the curriculum materials and teacher workshops may need to be revised to place more emphasis on this idea.

CONCLUSIONS

I cannot make broad generalizations with the results from this study due to the small number of teachers and lack of control over a number of variables. However, there does appear to be sufficient evidence to say that middle grades teachers with limited preparation (a one-week professional development workshop) are able to develop an understanding of the purpose and context of the EDP and express that to their students. In some cases, teachers even present some sophisticated notions of the central ideas of the EDP and are able to relate it back to their students' prior knowledge or experiences. Some teachers related the EDP to the scientific method highlighting the connections they make to other disciplines. The goal, in part, of this research is to dispel the idea for teachers that engineering is "over my head" or something "I'm no good at" and for teacher educators that engineering needs to be taught by engineers.

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AUTHOR

Morgan Hynes is a Research Assistant Professor in the Tufts University Education Department and Education Research Program Director for the Tufts Center of Engineering Education and Outreach. Hynes received his B.S. in Mechanical Engineering in 2001 and his Ph.D. in Engineering Education in 2009 (both degrees at Tufts University). In his current positions, Hynes serves as PI and Co-PI on a number of funded research projects investigating engineering education in the K-12 and college settings. He is particularly interested in how students and teachers engage in and reflect upon the engineering design process. His research includes investigating how teachers conceptualize and then teach engineering through in-depth case study analysis. Hynes also spends time working at the Sarah Greenwood K-8 school (a Boston Public School) assisting teachers in implementing engineering curriculum in grades 3–8.