Using the Engineering Design Process to Complement the Teaching and Learning of Mathematics

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With the recent development of the Common Core State Standards for mathematics, teachers have now been recommended a set of standards that cover not only the content of their mathematics classrooms, but also the practices with which to engage students as they learn that content[1]. Though this newest incarnation of standards has been the focus of much attention, these process standards have existed in recommendations for the mathematics classroom before[2]. These practice standards include objectives such as “make sense of problems and persevere in solving them”, “use appropriate tools strategically”, and “look for and make use of structure”. While these standards are focused on the mathematics classroom, they are not exclusive to the mathematics classroom. Within the domain of engineering, the Engineering Design Process[3] is used to guide engineers as they solve problems. The eight practice standards contained within the Common Core standards share many similarities to the Engineering Design Process (EDP). As mathematics teachers look for ways to engage their students in these mathematical practices, the EDP can be leveraged as a way to encourage students to simultaneously think as a mathematician, and as an engineer.

Frameworks for Mathematics and Engineering

When the new Common Core State Standards for Mathematics were released, there were two main features of the standards, the content standards and the practice standards[1]. The content standards were lists of mathematics content, organized by grade level and content area, which students were expected to learn in their mathematics classrooms. In addition to these grade-level content standards, there were also standards of mathematical practice that cut across grade levels (See Table 1). These standards described mathematical habits of mind, which are important for critical consumers of mathematics content.

MP1 - Make sense of problems and persevere in solving them
MP2 - Reason abstractly and quantitatively
MP3 - Construct viable arguments and critique the reasoning of others
MP4 - Model with mathematics
MP5 - Use appropriate tools strategically
MP6 - Attend to precision
MP7 - Look for and make use of structure
MP8 - Look for and express regularity in repeated reasoning

Table 1 – Standards for Mathematical Practice (NGA, 2010)

What becomes apparent when reading these practice standards is a shift in mathematics classrooms. The traditional mathematics classroom of lecture and exercises don’t lend themselves to supporting students engage with these mathematical behaviors. Instead, a problem solving and investigative approach to mathematics is most conducive to engaging students in these behaviors[4]. This approach requires complex, worthwhile problems to investigate, where students have opportunities to conjecture, reason, and evaluate solutions.

The field of engineering is one that concerns itself with solving real world problems and draws upon knowledge of mathematics and science to do so. Engineering tasks give learners opportunities to apply and extend their thinking to solve problems and achieve goals. In classrooms, project-based learning experience[5] afford opportunities to consider rich problems, and apply mathematical, scientific, and technological understandings. Just as the mathematical practice standards highlight habits for students to engage with, so too does engineering have a process for investigating. The engineering design process describes a cyclical series of stages common for engineering investigations when working to achieve an engineering goal (see Table 2).

Ask: Identify the need and constraints
Research the problem
Imagine: Develop possible solutions
Plan: Select a promising solution
Create: Build a prototype
Test and evaluate prototype
Improve: Redesign as needed

Table 2 – Engineering Design Process (TeachEngineering, 2016)

At a large private university in the northeast of the United States, graduate students with a strong mathematics background can enroll in a one-year mathematics education degree program where they can earn their Masters of Arts in Teaching degree as well as their teacher licensure certification. As part of this degree program, graduate students enroll in classes focusing in content and pedagogy, and also have practicum experiences where they student teach in local schools. This university also offers a program focusing on supporting the integration of engineering expertise in mathematics classrooms by recruiting those with engineering experience to become mathematics teachers. For students accepted into this program, in addition to the coursework required for their degree, there are also seminars offered which attempt to more explicitly connect the work and experiences of engineers to that of the K-12 mathematics classroom. There are five seminars offered over the course of the program and range in topic to include engineering, technology, curriculum, professional communities, and other aspects of interest to new teachers.

This paper describes an activity used in one of these seminars to connect the Engineering Design Process to the content and process standards in the Common Core State Standards. In this session, 10 engineering undergraduate students and 10 beginning mathematics teachers participating in the special program worked together to solve an engineering design challenge by using the engineering design process. Discussions after the task focused on the work of mathematics teachers, and specifically how the Common Core State Standards and the Engineering Design Process (EDP) mutually support each other and can be integrated into the mathematics classroom to support the development of students' mathematical skills. The undergraduate engineering students had been working on developing different versions of these Engineering Design Process challenges to use with teachers and students. This activity was not one that the session participants had experienced before.

Engineering Design Challenge

The activity used with these engineers and beginning mathematics teachers was project based learning experience where participants attempted to solve an engineering problem by drawing upon their mathematical, scientific, and engineering experiences. The goals of this project were to build a tower that could support a marshmallow, optimizing the height of the tower, while also minimizing the cost of the tower's supplies (See Figure 1 for text of the task).

Engineering Design Challenge: Marshmallow Tower

Challenge: Create the tallest freestanding tower that can support a marshmallow.

- Keep it cost efficient, a low $ per inch of height ratio
- Teams of 2
- It cannot be fixed to the ground
- Must be freestanding
- Tower is measured from bottom to the top of the marshmallow

Materials

- Max 20 pieces of pasta: Spaghetti - $50 per piece, Fettuccini - $75 per piece
- 1 yard of tape: free
- 1 yard of string: free
- 1 marshmallow: free

Figure 1 – Text of Engineering Design Challenge Task

Participants in the session were first introduced to the EDP, reviewing the different phases including identifying the problem and constraints, developing possible solution paths, selecting a path and building a prototype, evaluating the process and making improvements. Attendees began by working in pairs (one engineering undergraduate student and one mathematics education masters student) to design their towers and plan how to spend resources for their towers (see Image 1).

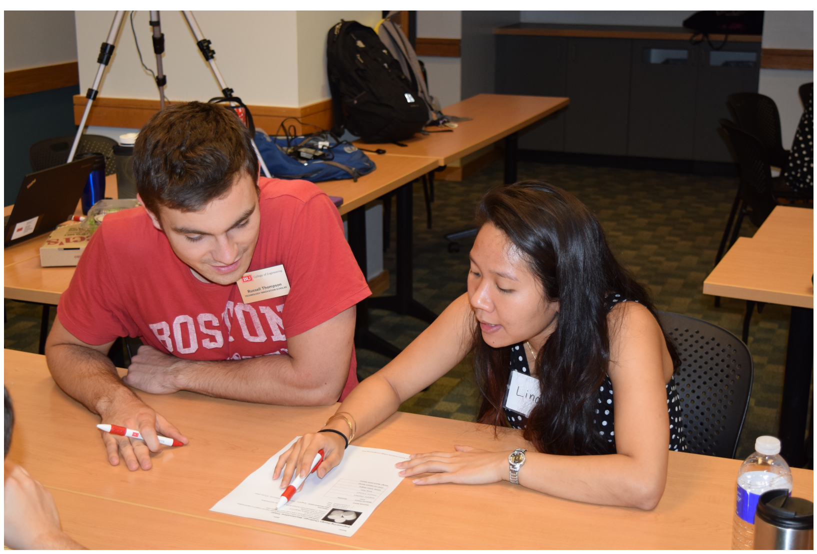

Image 1 – Planning the Tower

After this initial designing period, pairs then transitioned to creating, constructing, testing and improving their towers in an iterative process (see Image 2). When the engineering students and beginning teachers attempted to use the tape and string as connection materials in the towers many soon found themselves revising their original tower plans and redesigning based on what they discovered to be the physical properties of the connective materials. Participants were limited to using only their partner as resources and could make as many attempts as they wanted during the 30 minutes allotted for the activity.

Image 2 – Building the Tower

At the end of the construction phase, one of the session leaders went around and measured the heights of the marshmallows being supported by the towers. They also collected the total cost of the construction for the towers. With this information, the session participants looked at who was able to produce the tallest tower, who had the least cost per inch of height in their tower, and the tower design of these towers.

After the direct investigation of the tower comparison was concluded, the session participants reflected on this engineering design task and looked at the ways it connected to the mathematics classroom. The engineering students and beginning teachers engaged in conversations about the mathematical content of the engineering task, as well as the connections between the EDP and the standards of mathematical practice.

With this one activity there were discussions about the various mathematical ideas that could emerge through this activity. Geometric ideas around measurement (i.e. angles and lengths), 2-dimensional shapes (ex. triangles, polygons, etc.) 3-dimensional shapes (ex. prisms, pyramids, etc.), similarity and congruency, and visual and spatial reasoning emerged. Additionally, algebraic ideas around systems of linear equations, optimization, and rates also were discussed. Many different pieces of mathematics content that this activity addressed were identified and the session participants examined how a single activity, such as this, could be strategically used in classrooms as powerful investigations that could be referenced at multiple times throughout a course.

One of the key moments of this experience occurred near the end of the reflection when the engineering students and the beginning teachers reflected on the engineering design process they implemented during the activity. They compared this to the mathematical practice standards they are expected to implement throughout their classrooms. What occurred during this discussion were many connections among the different aspects of these two descriptions. They saw connections between the mathematical expectations to make sense of the problem and the engineering process of identifying the needs and constraints. They linked the mathematical standards of reasoning abstractly and constructing viable arguments to the engineering processes of developing possible solutions and selecting promising solutions. With the mathematical standards of modeling with mathematics and using strategic tools appropriately, the engineers and beginning teachers saw connections to building, and testing, a prototype. Lastly, by attending to precision and critiquing the reasoning of others in the mathematics standards, this group saw connections to the engineering standards of evaluating the prototype and redesigning as needed. Ultimately, participants felt that there was significant overlap between the EDP and the work they were doing already in their classrooms to engage students with the standards for mathematical practice.

Discussion

In the Mathematics Knowledge for Teaching framework, different kinds of knowledge important for the teaching of mathematics are described[6]. Among these is horizon content knowledge, which includes the knowledge of how math content is connected to the mathematical content of prior and future grade levels. Horizon content knowledge also includes how mathematics content in a grade level is connected to the content of other subject areas at the same grade level. The connection between mathematics and engineering is an important link to support the STEM education of all students.

Beyond the recommendations for mathematical content that is to be taught in K-12 schools, there are also recommendations for standards of mathematical practice[1]. These standards reflect skills and dispositions that mathematics students should have emphasized through their education from kindergarten through high school and include making sense of mathematical problems and persevering in solving them, construct viable arguments and critiquing the reasoning of others, and the use of appropriate tools strategically. Teachers are being recommended not just the mathematics content that K-12 students should know by the end of high school, but also the mathematical expertise that students should be proficient with. There is much work to be done in supporting teachers (both beginning and experienced) emphasize these standards of mathematical practice more explicitly into their instruction.

There are great benefits for teachers to utilize engineering tasks, and the engineering design process in their mathematics classrooms. First, it provides students with authentic mathematical problem solving opportunities where they can apply and extend their understanding of mathematics content. Additionally, the formalized engineering design process supports a structure of investigations that highlights hypothesizing, investigating, experimenting, analyzing, reasoning, and reflection. These are skills that are not just important when working on engineering tasks, but also mathematics tasks. The EDP supports students learning of the mathematical practice standards.

By utilizing an engineering design tasks, engineering students and beginning mathematics teachers were able to have rich discussions on the similarities of two scientific fields. Their discussions revealed an understanding of mutually beneficial goals and highlighted opportunities to leverage the work done in the field of engineering to support mathematical standards of learning. Engaging future teachers in these experiences are one way to support teachers as they work to incorporate authentic investigations, group work, and the implementation of mathematical practices. This paper presents just one example of how the teaching and learning of mathematics can be strengthened by incorporating ideas from engineering. The engineering design process can be utilized with students to engage with key ideas of investigating and problem solving as they work toward a greater understanding of content and more richly connected habits of mind.

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