Cardboard boat building in math class

This article examines how the implementation of an integrative learning experience encouraged middle school students to work collaboratively, and apply their knowledge in relevant and meaningful ways.

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If you want to get the attention of a group of eighth grade math students, tell them they are going to build a life-size cardboard boat. To increase interest, follow up this statement by telling them that two to four of them will actually be rowing this boat across a small pond. You will likely hear replies such as, "You're nuts," and "I'm not getting in that boat," or even, "You have lost your mind." But you may also notice excitement, a willingness to try, and wonder in the eyes of students.

Eighth grade math students at Oasis Charter Middle School in southwest Florida have completed this project for the past four years. What has now become a source of great student pride at the school began as a challenge by the eighth grade teachers to their students. The teachers sought to develop a capstone project, which brought together the key mathematical issues students should learn in their middle grades math classes (i.e., scale, volume, Pythagorean theorem). They also desired a project to engage students in the STEM (science, technology, engineering, mathematics) disciplines to help young adolescents develop skills necessary to thrive in a 21st century workforce. As a result, the cardboard boat challenge was created and implemented. In this article, an overview of STEM education is shared, along with a discussion of the struggles and triumphs of the eighth grade students as they planned and built their cardboard boats.

STEM education and the challenges of the 21st century

With increasingly new technologies, and a rapidly expanding knowledge base, the twenty-first century is changing how K–12 schools educate students. They can no longer expect that information they learn in a technologically-based class will be up-to-date a few years into the future (McLeod, Fisch & Bestler, 2009). As a result, young adolescents must understand how to think critically, problem solve, and collaborate with peers to overcome the challenge of a rapidly changing knowledge base; in essence, allowing students the opportunity to "make sense of the world rather than learn isolated bits and pieces of phenomena" (Morrison, 2006, p. 4). Further, policymakers claim that if students do not emerge from K–12 schools with the ability to enter the workforce understanding innovation, scientific knowledge, and the ability to discover new ideas, the economy of the United States will suffer (Committee on Prospering in the Global Economy of the 21st Century, 2007). Albert Einstein is quoted as saying, "We can't solve problems by using the same kind of thinking we used when we created them," which summarizes the challenge of the new century in which middle school students must be able to look beyond current knowledge and work together to creatively construct novel solutions to unique problems.

Unfortunately, many students are being turned away from entering the STEM fields once they enter college. This absence has been represented in literature using an analogy of a leaking STEM "pipeline" (NCES Digest of Educational Statistics, 2008). The leaking in the pipeline occurs at a variety of places, including high school and college (NCES Digest of Educational Statistics, 2008). Research findings have shown students leaving STEM fields for a variety of reasons, including an absence of a proper knowledge base and lack of interest in the field (American Association of State Colleges and Universities, 2005). A lack of diversity persists in the individuals receiving degrees in STEM fields, with women and minorities being much less represented (Blickenstaff, 2005; Katehi, 2009).

According to a recent report from the White House, the United States graduates approximately 300,000 bachelors and associates degrees in STEM fields in the United States annually (PCAST, 2012). Further, PCAST (2012) states, "Fewer than 40% of students who enter college intending to major in a STEM field complete a STEM degree" (p. i). A 2011 report by the Office of Naval Research furthers this statistic by stating only 6% of high school seniors will get a bachelors degree in a STEM field (Office of Naval Research, 2011). In fact, the United States awards only 15% of bachelors degrees annually in the STEM fields, a ranking of twenty-seventh in the world (U.S. Congress Joint Economic Committee, 2012). According to the PCAST (2012) report, one million additional STEM professionals will be needed over the next decade; to meet this demand, the number of students who earn STEM degrees will need to increase by 34% annually when compared to current rates.

This so-called leaking pipeline and the small number of STEM graduates are the impetus for calls for the development of STEM education programs in K–12 schools across the United States. Recently, the educational community has been using the word *integrated* in many definitions of STEM education to try to return the focus to the connectedness inherent in the four disciplines. Historically, the disciplines of science, technology, engineering, and mathematics have developed their own independent curriculums in schools and have not worked together to show the integrated nature of the subject areas (Sanders, 2009). However, the diverse kinds of work of professionals in STEM careers blur the lines between the disciplines (Wang, Moore, Roehrig, & Park, 2011). Due to the actual nature of work in these fields, some educators are pushing for the integration of these subjects into interdisciplinary programs in K–12 schools. According to Smith and Karr-Kidwell (2000), an interdisciplinary curriculum is holistic, and links the disciplines by highlighting relations and connections. While the idea of an integrated and interdisciplinary curriculum is not unusual, applying this type of curriculum to STEM education is quite new (Stohlmann, Moore, McClelland & Roehrig, 2011). Sanders (2009) defines STEM education as, "our notion of integrative STEM education includes approaches that explore teaching and learning between/among any two or more of the STEM subject areas, and/or between a STEM subject and one or more other school subjects" (p. 21).

The engineering component is a key element that can help easily integrate the four STEM subjects due to the nature of the discipline. Morrison (2006) states that major misconceptions regarding STEM education revolve around the role of engineering education; it is believed that engineering should be included as additional coursework, and that it is disparate and troublesome to be included in the general education curriculum. However, these misconceptions might be overcome by looking at the power that engineering education provides in allowing for a truly integrated curriculum. Specifically, Katehi (2009) claims, "Engineering education could be a catalyst for more integrated, and effective, STEM education in the United States" (p. 3). However, while scholars call for more engineering classes in K–12 education, these classes are not commonplace. Specifically, Bybee (2010) states, "Engineering has some presence in our schools, but certainly not the amount consistent with its careers and contributions to society" (p. 30).

Development of the cardboard boat challenge

The eighth grade teachers at Oasis Middle collaborated to develop the Cardboard Boat Challenge in an effort to make math classes more engaging, dynamic, integrative, and relevant. The challenge was designed with two major aims. First, to act as a culminating project of the mathematical skills the students learned throughout middle school. This goal also was tied to the state standardized assessment for the first group that completed this project. The eighth grade group that completed the first cardboard boat challenge had extremely low standardized test scores, with just over half coming into eighth grade at or above grade level. By completing this project, students reinforced skills they had learned in previous years, and they paired mathematical theory with mathematical practice. The hope was that by becoming fully invested in mathematics and having concrete practice with the skills, the students' mathematical knowledge and understanding would increase.

The second aim of the project involved increasing student engagement in STEM fields. The teachers were aware of the analogy of the leaking pipeline and of the efforts to increase student interest in the STEM fields. However, they questioned why most of these efforts took place primarily with high school students. By bringing an engineering task into the middle grades mathematics classroom, student engagement could begin earlier. Students in the middle grades need to be active in their learning. By harnessing this natural curiosity, students' knowledge of engineering and mathematics might increase. The teachers found, as mentioned by Katehi (2009), that engineering projects are an effective catalyst for integrated education. By working through and with engineering, mathematics in these classrooms became much more pertinent, purposeful, and powerful.

The challenge

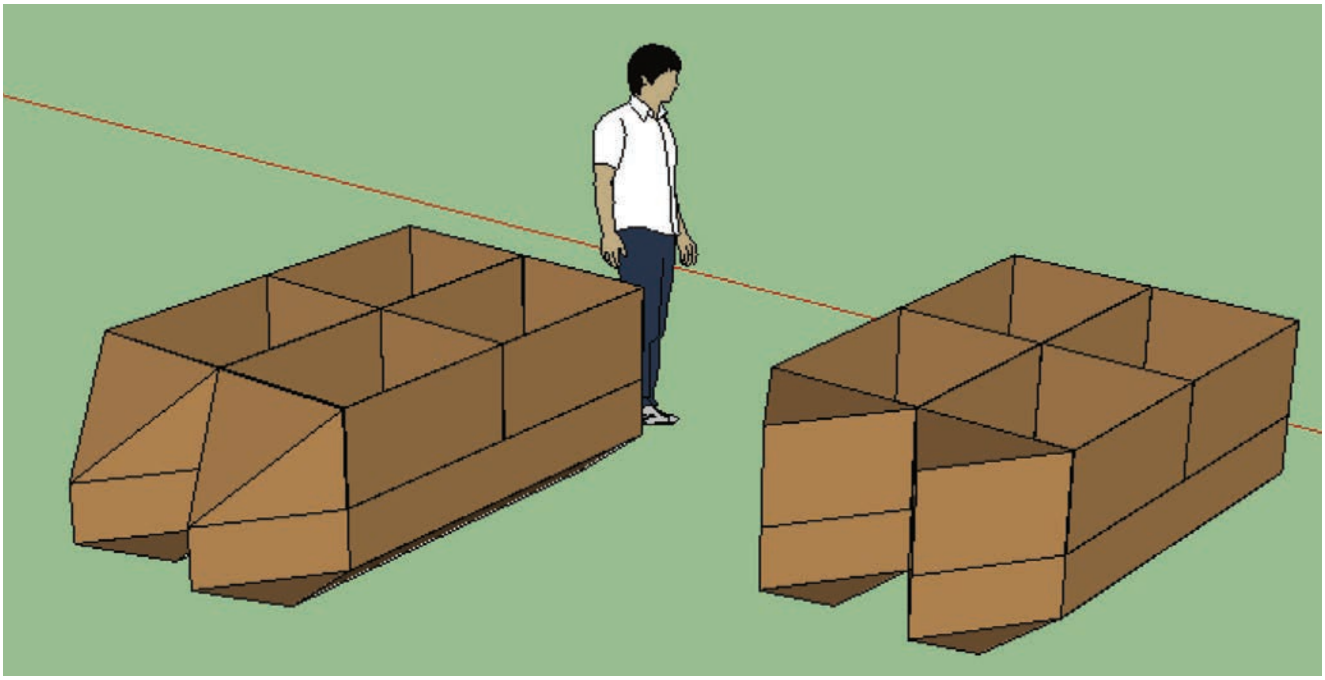
The Cardboard Boat Challenge was relevant for this school for two major reasons. First, the community in which the school is located hosts an annual cardboard boat regatta. Therefore, an additional regatta for the school naturally allowed students to relate to the challenge. Further, the community of the school has a large boating population due to more than 400 miles of canals in the city. As a result, many students are familiar with boating and engage in it as a pastime.

The challenge was divided into three distinct phases that took place over the entirety of a semester, with small amounts of time each week devoted to working on the boat challenge. The work was separated in this way to minimize the enormity of the task for the students. The three phases were design, construction, and launch.

Phase 1: Design

In the design phase, students developed a scale drawing and scale model of their boat. In doing this, the major mathematical skill of understanding scale was reinforced in a relevant manner. Students formed groups of two to four members for this part of the project. The students were given the following constraints to follow in designing their cardboard boat:

Google SketchUP Design



- The design must be able to hold two to four people
- The design must showcase at least three distinct geometric solids
- The design must be able to fit through the doorway of the classroom
- The only permitted materials are cardboard, duct tape, and waterproof sealant

These constraints were meant to emulate the challenges often faced in real-life whereby limited resources exist or specific guidelines must be followed. When given a project at a job, very rarely is complete freedom afforded to the person. Therefore, the teachers felt it necessary to provide parameters to the students. Also, by requiring three distinct geometric solids, the teachers aimed to reinforce spatial reasoning.

The students had to determine appropriate dimensions of their boat with little guidance from their teachers. Developing independence was another aim of the project—a skill teachers sought to help develop during the entire experience. To determine the dimensions, the students took tape measures and acted out being in a boat. As a result, a number of noteworthy discussions took place among the students. For example, one of the most common discussions pertained to how people would sit in the boat. If people sat with their legs extended, it would be a very different length than if they sat on their knees. The students had conversations about the stability of the boat and rowers versus the length. While having people kneel would make the boat shorter (and faster according to the students), they were concerned about the stability of the boat. These conversations and musings came naturally, and they provided valuable learning opportunities for all students involved.

After the students designed preliminary sketches, they were asked to create an orthographic projection of the boat—a sketch of the boat from the top, front, and side. This task required a great deal of geometric understanding as they were transforming a three dimensional sketch into three, two-dimensional drawings. Students had to ensure that the scale dimensions of all three views matched up, and they had to visualize a three-dimensional object and view it from three distinct viewpoints. To aid the students in this task, the teachers asked the students to construct their design in Google SketchUp, a free online computer-assisted design software. By drawing their three-dimensional image in the program, the students were able to manipulate the boat virtually and truly see what the different projections looked like. Finally, they were asked to create a scale model of their boat for display. Again, the students were required to take their drawings and transform them into actual three-dimensional models. A great amount of geometric and spatial knowledge was being reinforced through this experiential and hands-on approach.

Once the sketches and models were complete, the final task in the design phase required that students use a series of mathematical formulas involving volume and surface area to compute the amount of weight the boats could hold once constructed. This activity had the

Boat made by students

Boat made by students

students determining a true application for surface area, volume, and buoyancy. It became apparent why these concepts were necessary when doing these calculations. Further, because some students would be in one of the boats, and they did not want to end up sinking and in the water, the students became extremely precise and rigorous with their calculations.

Phase 2: Construction

After the small groups developed their drawings and models, the class came together to decide which boat to construct. As it was not possible to build all the boats in the classroom, the student groups presented their boat designs to the class and explained why they believed theirs was the best. After the presentations, the students voted via a ballot for the two boats they felt had the best design. The one boat that received the most votes was declared the winner and was constructed.

As with the project as a whole, the construction of the boat was broken into smaller pieces due to the enormity of the project. The students had to identify major components of the boat (i.e., rectangular prism body, pyramidal nose, etc.), and these components were listed on the board. Groups were then developed, and were solely responsible for constructing one of the figures listed on the board based on the scale drawing. A group leader was selected for each of the construction groups. These group leaders were responsible for communicating between the groups because while the students were building one component in their groups, that component had to fit perfectly with the other components in order to be seaworthy. As a result, the students needed to work closely together to accomplish the goal.

In the construction, the role of the teacher was that of cardboard cutter. The teachers only cut what the students gave them. They continually reminded students to, “measure twice and cut once.” The teachers offered no other concrete advice on the actual construction (except in cases of mathematical learning), which required the students to depend on one another. As mentioned earlier, this helped develop camaraderie and collaboration among students as well as less reliance on teachers. This was incredibly difficult for some students to deal with at first, as they felt the teachers were not doing their job by not answering all of their questions and not, “Giving the answer.” However, a significant transformation occurred after a week or two of having the students rely on each other. The students in the classes began depending on one another and asking peers the questions they would have normally asked their teacher. Consistent with the ideals of exemplary middle level education, the students thus became facilitators, partners, and leaders.

The actual construction of the boat proved to be more of a learning experience than any of the teachers had expected. While they felt that the students would develop a greater understanding of scale and spatial reasoning, the depth of knowledge that was generated and reinforced in the project proved to be remarkable. One noteworthy example pertains to the connection students made between the circular base of a cylinder and the circumference of a circle. Many student groups decided that having outriggers on one or both sides would help with the stability of the boat. A few of the groups decided to make these outriggers cylindrical. Students in these groups started by making the circular bases for the cylinders; however, they soon encountered a roadblock when they had to make the curved body connecting the bases. This provided an ideal learning opportunity. Teachers brought the class together and discussed with the students the net for a cylinder (two circles and a rectangle). Discovering that the curved body was really a curved rectangle proved to be essential in the construction of the cylinders. Teachers further led students to understand that the length of the rectangle was equivalent to the circumference of the circle by doing things such as peeling the label off of a cylindrical can. Once students realized this, they were able to apply this knowledge and determine the circumference of the circles, which allowed them to measure the appropriate length of the rectangles.

A second common learning experience that emerged involved students learning the relevance of the Pythagorean theorem. Several groups decided to make a nose for their boat in the shape of a square-based pyramid. While the groups knew the overall height wanted for the nose, the difficulty came when they were trying to make the triangular faces for the pyramid.

Boat made by students

This presented another relevant learning opportunity to discuss the relationship between the Pythagorean theorem and the slant height of the pyramid. Bringing the students together, the teachers discussed how, knowing the altitude and length of the square base, the students could apply the Pythagorean theorem to determine the slant height of the triangular faces. Equipped with this knowledge, the students were able to transfer the skill to their design and accurately measure and construct the four triangular faces of their pyramid.

Once the pieces were individually constructed, the students worked to piece the shapes together for the final construction of their boat. The students then had an opportunity to decorate the boat with any theme they wanted. In the construction, each period used 30–50 rolls of duct tape and hundreds of pounds of cardboard. But the relevant and engaging learning experiences that emerged far outweighed these materials.

Phase 3: Launch

To build interest and energy for the project, the launch day was named the Oasis Boat Regatta. Families and the community were invited to the school to watch the launch. As the middle school is part of a K–12 charter school system, the elementary and high schools were encouraged to come and cheer on the eighth grade students. The support for the eighth graders who built the boats was important; they deserved recognition for their hard work. The first year, more than 500 people watched the race, with this number nearly doubling the second year of the race.

The students competed in heats with one boat per teacher racing at a time. The times that it took for students to cross the pond were recorded; if a boat did not make it across the pond and sank, the team was given a time of the highest recorded time plus five additional minutes. All students who raced the boats were required to wear life vests and be able to swim in open water, as the pond used could be as deep as 15 feet in certain spots. Further, all students who raced in the regatta had waivers signed by their parents, which indicated the student's ability to swim and provided permission for the student to participate, knowing the boat may sink. During the races a lifeguard was present and several teachers were stationed around the pond to assist students whose boats sank get to shore. In the end, mean times were calculated for each teacher's team, and the teacher's team with the lowest mean time was declared the winner of the regatta.

In the first year of the races, the students with the lowest standardized tests scores had the fastest times. The classes with the highest standardized test scores had the fastest times in the second year of operation. This showed the teachers, as well as the community at large, that these exploratory, relevant, integrative, and challenging projects do not have to be reserved for students with high scores on standardized tests. Students who may struggle in a traditional paper and pencil environment can thrive in a more engaging, dynamic, and non-traditional classroom format. All classes did the same mathematics in creating their boats and, as a result, all were able to show their mathematical understanding through this project.

Conclusions

This engineering task proved to be an engaging experience that helped eighth grade students develop an understanding of mathematics and its relevant application. By being actively involved in the process of designing, constructing, and launching a boat, students developed an understanding of the necessity of the knowledge and skills related to the middle school mathematics curriculum. Encountering obstacles during the construction process helped students learn to become more independent from teachers and rely on their peers instead of going to their teacher. The teacher was eventually used as a last resort in this project and became a facilitator for student learning. When mathematical concepts were needed to proceed, the teacher guided the students to the knowledge they needed to proceed. With the developing knowledge, the students were able to apply their understanding and skills, and complete their constructions.

This task provided engagement for all levels of students. It allowed for true student- and discipline-centered learning, and provided challenging curriculum for all levels of students. Further, in the first year of operation, it allowed students with the lowest test scores to win the entire regatta. This project allowed them an alternative way both to access the curriculum and showcase their knowledge.

All students seemed visibly excited throughout the project. All students were continually engaged because of their interest in the project, and the amount of work to be completed. Due to student engagement, this project led Oasis Middle School to develop an interdisciplinary STEM Academy for students. This program is currently in its fourth year of operation with more than 150 sixth through eighth grade students participating. The hope is that by working with an engineering mindset, and engaging students this way in all classes, students will be able to develop the necessary and important skills of problem solving, critical thinking, and collaboration to help build successful lives in both the present and the future.

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