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How to Use Engineering in High School Science: Two Case Studies

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How to Use Engineering in High School Science Teaching: Two Case Studies

Abstract
The recognition of engineering-based pedagogy has been embraced by many advocates at the national level. Massachusetts has been the first state to mandate the use of engineering in K-12 curricula. More recently, the NGSS (Next generation Science Standards) draft and Common Core standards also embrace the engineering-based pedagogy. Typically, the use of engineering in high school teaching centers around using the engineering design process in the classroom. The authors have observed over a three-year funded research project that biology and chemistry are the hardest STEM subjects to implement the engineering approach, unlike other disciplines such as physics, math, and engineering subjects. This paper describes two case studies of two teachers, one teaches zoology and the other teaches biology. The paper outlines each case study, the teacher implementation, classroom results by students, and the students' feedback and evaluation of the engineering-based learning model.

1 Introduction

In recent years, there has been a concern for the decline in K-12 students interested in pursuing STEM (science, technology, engineering, and mathematics) majors in higher education. There has also been a strong concern to why STEM interest has steadily declined. These recent trends are cause for great angst because without students' pursuit of STEM education, the possibility of future innovation also declines. Previous efforts to improve STEM education and increase student interest have often reverted back to known teaching methods like T4E (Teaching Teachings to Teach Engineering) and well-known problem-based learning (PBL) [1, 2]. However, the effectiveness of these methods lies in changing teachers' current pedagogies rather than modifying the actual content of how teachers teach. To help address this situation, we have designed a method to educate teachers in a two-week professional development workshop [3, 4]. Teachers learn how to properly integrate engineering techniques to modify their current teaching content. We make a case that the integration of particular engineering methods in STEM classrooms can make an impact and change the way students perceive STEM content.

Past literature has stated that students, as early as middle school begin to gravitate toward academic subjects they find interesting [5]. Specifically in high school, students are developing stronger interest or disinterest in STEM subjects. This ultimately widens the gap between those students who enjoy math and science versus those who do not enjoy those subjects. We believe the lack of interest of those students who do not find STEM appealing is due to how STEM content is delivered from teacher to student rather than a true disinterest in the subject content. Current teaching methods use a traditional top-down approach of lecture and textbook reading. Unfortunately, student-learning methods have undergone a paradigm shift in how they learn. Past teaching pedagogies no longer engage students' interest and we must find alternative methods to educate them on the importance of STEM in education and in their life.

Without a thorough understanding of how STEM is involved in students' lives, students fail to make connections with why STEM theory is important [6]. With no development of formative relationships, students lose interest and fail to pursue additional STEM education thus, jeopardizing our educational competitive edge with other countries [6, 7]. Current teaching STEM pedagogies need to be more modular in order to address the changing needs of how students learn and interpret information [8-10]. We believe a partial solution to this situation is twofold: 1) By introducing common engineering practice in STEM teaching, engineering methods can have a great impact on how students perceive their environment; and 2) Engineering techniques in traditional STEM courses enhance student ability to critically think and analyze open-ended problems.

The authors have observed over a three-year funded research project that biology and chemistry are the hardest STEM subjects to implement the engineering approach, unlike other disciplines such as physics, math, and engineering subjects. This paper describes two case studies of two teachers, one teaches zoology and the other teaches biology. The paper outlines each case study, the teacher innovative thinking, the classroom implementation by the students, and the students' feedback and evaluation of engineering-based learning model.

2 Benefits of Engineering in High School STEM Teaching

According to a report published by the National Academy of Engineering (NAE) and National Research Council (NRC) Center for Education, engineering in K-12 education has received little attention [10, 11]. As of 2009, there was an estimated 18,000 teachers that have attended professional development sessions to better understand and experience engineering-related coursework in K-12 settings [10]. According to both the NRC and NEC, they believe that the implications of engineering education could be a catalyst for a more integrated and effective STEM K-12 education in the United States [10].

Engineering provides students with hands-on learning approach in the classroom. Pedagogical research implies that K-12 students learn best by engagement and interactions that directly relate to their daily lives [12, 13]. By incorporating hands-on activities in the classroom, it reinforces basic theoretical STEM principles and allows students to understand the applicability of STEM concepts. Massachusetts has been the first state to mandate the use of engineering in K-12 curricula with a focus on using the engineering design process (EDP) as a framework to solve open-ended problems [14, 15]. More recently, the NGSS (Next Generation Science Standards) draft [16] and Common Core standards [15] have also embraced engineering-based curriculum. The Common Core standards specifically have emphasized strategic-based problem-solving with a concentration on hands-on, design based learning integrated within traditional STEM education. Engineering-based pedagogy has been recognized as one of the new and effective teaching pedagogical methods that can bridge the gap between abstract STEM concepts and their use in students' daily lives, thus changing the way students understand STEM education and careers.

In order to support the local state and national initiatives of integrating more engineering in STEM classrooms, there needs to be strength and efficacy in the development of those methods. In other words, not every method will be successful in engineering integration. However, if pedagogies are introduced to teachers correctly, engineering integration can be enormously effective in translating the usefulness and need of engineering in STEM K-12 classrooms. Similar to K-12 teaching, professional developments are also all about how the content is delivered. How the new teaching pedagogy methods are delivered will determine if teachers adapt those methods in their classroom. Professional developments are the portal to change and impact current teaching methods and styles. By providing an effecting training platform, we can effectively modify how STEM content is delivered to students.

Engineering is about the development of something new, the development of a new solution that is either new or an improvement on an existing solution. The claim is not to make every student an engineer. Nor is it to make every teacher an engineer. But the goal is to improve students' ability to think critically and understand how to solve problems that do not necessarily have a right answer. The development of students' ability to think critically is most prevalent when students are learning how to think and analyze problems [6, 17, 18]. There is such focus on standardize tests and *getting the right answer*, that students lose sight of what school and education should be about. Hand-on activities that pose an open-ended challenge force the mind to think, not only about the answer, but the process on how to get there. Engineering integration has the possibility to intertwine not only math and science but also art and creativity. Every students should have the change to engineer [19] and experience the process of student-centered learning. Engineering enables students to be challenged and "tackle ill-defined problem and lead them to direct their own research on a problem that ends with a successful solution" [19].

3 Use of Engineering in High School STEM Teaching

The use of engineering in high school STEM teaching utilizes the engineering design process (EDP) as the guiding principal. A teacher assigns students an open-ended problem as a project and asks the class to find a solution to the problem. The teacher divides the students in the class to teams of three to four students, much like a college capstone project. Students follow the EDP steps shown in Figure 1. A project can last from one week, to a semester, to a full year. The teacher decides the project length that best fits the curriculum requirements.

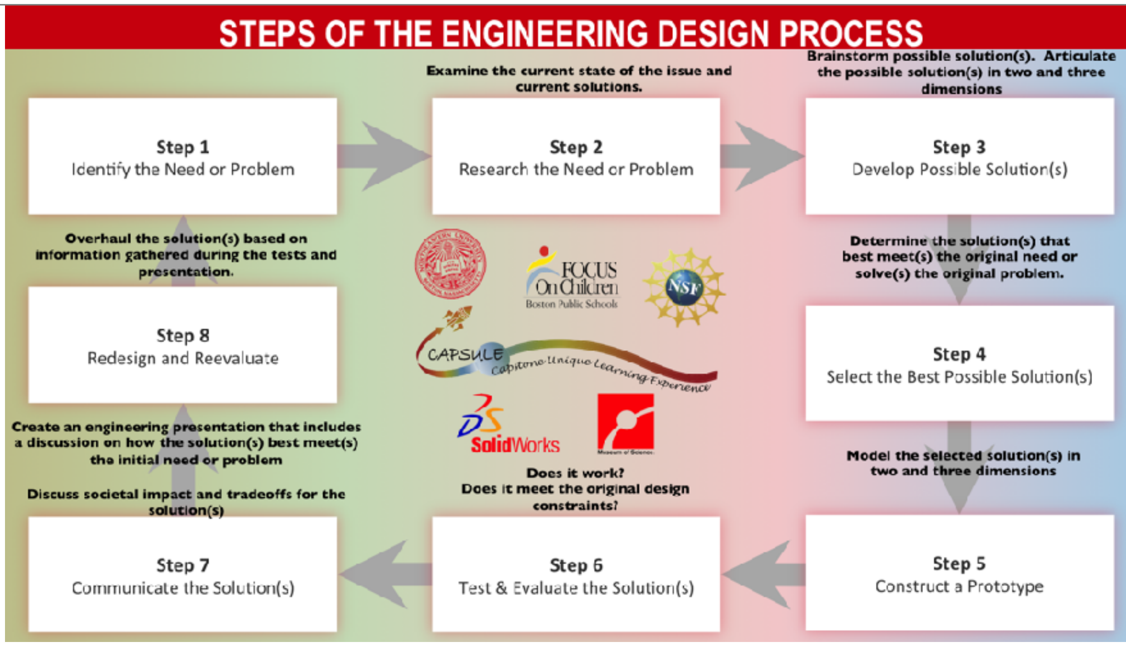

Figure 1: Engineering Design Process

The authors have run a three-year NSF funded research project to teach high school teachers how to use engineering in their STEM courses. The project runs a two-week professional development workshop for teachers. The first week focuses on covering the engineering pedagogy and how to use it in STEM teaching. The second week asks teachers to devise an implementation and lesson plans on how they envision integrating the new engineering methodology they learnt in the first week into their classroom teaching.

The authors have observed over the project three years that biology and chemistry are the hardest STEM subjects to implement the engineering approach, unlike other disciplines such as physics, math, technology, and engineering subjects. Biology and chemistry teachers find it particularly hard, but not impossible, to blend engineering to these subjects. One chemistry teacher was innovative enough to ask her students to take on cleaning a town water source in working with town officials. The remaining of this paper covers two biology courses of two different teachers.

4 Summary of CAPSULE Professional Development

The CAPSULE program was designed in response to the NSF initiative to encourage and create change in teaching pedagogy. The ITEST or Innovative Technology Experiences for Students and Teachers was created to engage K-12 students in authentic experiences that build their capacity, motivation, and desire to participate in more math, science, and engineering courses. Engineering-based learning (EBL) was created with a defined process, structure and tools. EBL, focused on the reverse methodology of finding/discovering a problem and critically finding a solution to a real-world problem. Very similar to college capstone courses, EBL was modified for K-12, but using equally as impactful projects in high school classrooms.

CAPSULE or CAPStone Unique Learning Experience was designed as a two-week professional development to educate teachers on the undergraduate engineering capstone model. We hypothesized that the engineering capstone model, that is required at all accredited engineering colleges would be an ideal methodology to implement in K-12 STEM due to the mix of lecture and hands-on teaching pedagogy. The two-week course was divided into two primary purposes. The first week focused on learning and understanding the theory behind EBL, the method, and the tools necessary to implement the pedagogy in the classroom. The second week was focused on developing implementation and action plans for their (the teachers') own classrooms. Each teacher attended the program with different objectives for their own classroom, but fully agreed with the purpose of bring and developing more engineering-based curriculum in their classrooms.

During the first week of CAPSULE, teachers experienced what being a student was like again. Participants learned and familiarized themselves with the engineering-design process (the structure), the capstone experience (the experience), and 3D modeling (the tool). Similar to the better known project-based learning (PBL), EBL was focused on more hands-on, interactive learning. However, the difference between PBL and EBL are the corresponding method and tools of EBL. The engineering-design process provides students and teachers a series of steps to assist in the design and development of a solution to a problem. Although there are associated "steps" of the process, each step is an open-ended guide. Participants used EDP to participate in their capstone-like experience be creating a solution to a provided problem. For example, in the final year of CAPSULE, the open-ended problem was *Design Your Dream Closet*. Of course, there were various constrains placed on provided problem (similar to real-world industry). Participants ended the first week with a culminating, true capstone-like experience with full capstone group design and engineering, a final 3D model built Solidworks™, and a final capstone poster. Each group then presented their final engineered solution on Friday of the first week [20-22].

The second week was focused on using engineering-based learning and the tools to modify the lesson plans for each teacher's individual classroom [20-22]. The second week was used to converse with colleagues, disucss with CAPSULE instructors, and design and develop capstone projects that reinforced core principals throughout the school year. Some teachers chose to create week-long capstone experiences while others, such as the ones discussed in this paper created multiple-week long capstone experiences. Each capstone experience has its benefits and detriments. The length of time truly depends on the constrains of the teachers and their classrooms. At the end of the second week, each teacher presented their implementation plan, their assessments (for both students and teachers), and a poster that documented their plan for the upcoming school year.

Teachers took what they learned through the professional development and applied them to various projects throughout the school year. Most teachers supported the fact that they were unable to run structured projects where they could entrust students to steadily progress without specific grading rubics or assessment milestones. With EBL, EDP, and Solidworks™, the pedagogy allowed students to focus on each stage of the design and development process of finding a solution to a given problem. EDP provided them the structure, capstone-experience provided them the end goal, and Soldiworks™ provided them the tool.

5 Case Study 1: Use of Engineering in a Zoology Course

In this case study, a science teacher at local high school reworked her teaching curriculum and teaching pedagogy to incorporate engineering (i.e. design the perfect zoo) in her zoology course via a zoology project application. The teacher had to integrate the EDP in to her course material to prepare her students for the project.

The Zoology class focuses on the biology of animals, understanding how their biological processes differ from humans. However, the capstone focused on an aspect of where animals live rather than their biological processes. The following statement was the given problem statement and project (open-ended challenge) respectively:

Problem Statement: The town has decided to convert a 49-acre site into a zoo to generate more revenues. The town would like to create 5 different designs for this project. At the end of the quarter, each design team will be responsible to "pitch" their design to the town community (your class). You will be a member of one of the design teams for this project.

Capstone Project: Design a zoo that utilizes the 49-acre site to house a minimum of 20 animals. Note: animals must be demonstrative of the following groups: invertebrate, osteichthyes, reptilia, amphibian, aves, mamalia. You must be respectful of the current ecosystems at the site. Part of your task is to design a zoo using the current land layout.

Table 1 shows the criteria that students were judged upon. The Capstone Experience Rubric represents how their grades were calculated based on the constraints. The Overall Capstone Experience rubric was simply to gather information on how the overall experience was. Because this class of students was the first year to complete the Zoology capstone, the teacher was looking for feedback on how to improve the process, the project, and the overall experience.

Table 1: Capstone Experience Rubric and Overall Capstone Experience Criteria

Capstone Experience Rubric (Scale 1-4, 4 = Exceeding Standards)	Overall Capstone Experience (Scale 1-4, 4 = Exceeding Standards)
Research Paper	Initiative
Zoo Map	Research
Overall Poster	Evaluation for Relevance
Presentation	Uses Resources Located
Overall Design	Citation
Town Member Evaluation	Participation
Animal Plaques	Productivity and Accountability
Community Redesign	Application

Students have six-weeks to complete this project, in groups of 4-5 students. Students were required to use engineering and had to report and analyze at each step of the EDP process to assure the systematic development of their progress. Groups were required to articulate their final decisions in a poster session and physical 3D model. They were also required to write a report. For their final presentations, all groups except one used a PowerPoint slide presentation to present their work. This class consisted of all juniors and seniors. **Error! Reference source not found.** Figure 2 shows three groups presenting their Zoology capstone solutions and their perspective of what their "ideal zoo" should have, the animals, and their respective design for patrons. Some of the authors of this paper were present during the student presentations.

For this science teacher and her students, the outcome was substantially better than expected for a first year capstone project. The six-week project was one of the longest projects ever developed, both for the teacher and her students. After students presented their work, we had discussion on the process, the theory reinforced, and the integration of engineering into science. There were multiple students who desired more time for the presentation because there was so much learned through the project and not enough time to share the knowledge they had learned. For some students, they were uncomfortable with the open-endedness of the project; partly because there were many different directions and which path was "right". That particular feedback reiterates the argument that students typically, always focus on finding the *right* answer rather than understanding the lessons are in the journey, not the destination.

Other students voiced the joy of freedom to explore and be creative in the project. Students were particularly surprised at the number of different designs that could result for the same problem. Additionally, students appeared to thrive in the "take charge of your learning" environment. For example, there was one group that researched zoos from Toronto, Canada to Miami, Florida, determining which aspects of each zoo they thought was most aesthetically pleasing, most functional, and would cater to the appropriate customer population. The group then took their collection of discoveries to combine them into a single final design. Similarly, another group solicited the assistance of a local contractor. They were seeking approximate (but true cost) of building the infrastructure of their proposed zoo.

Figure 2: Students presenting their Zoology Capstone

Many students reported that one of their least favorite aspects of their capstone was 3D modeling. Part of the criteria of their capstone was that students had to design their zoo in a 3D virtual environment. We believe part of the frustration with 3D modeling was due to their use of Google™ SketchUp and not Solidworks™. SketchUp™ has very limited functionality and for the complexity of some of their zoos, it is highly probable students were limited in their virtual design.

Overall, students enjoyed being challenged and in command of their own learning. For many students, it was significantly different than general lecture-based learning. Students also reported that the project was substantially harder than initially expected. Some students would have preferred a capstone project relating more to the biology of animals rather than “designing a zoo”. Although some students would have preferred a more biologically-based capstone experience, they did immediately acknowledge that they did use their knowledge of animal biology to design appropriate enclosures. This led to the realization and purpose of a capstone experience: everything is interconnected even though, on the surface, the goal looks to be defined.

6 Case Study 2: Use of Engineering in a Biology Course

In this case study, a biology teacher at a local high school reworked her teaching curriculum and teaching pedagogy to incorporate engineering in her AP biology course. This AP biology course was focused on preparing the students for the AP biology exam. The challenge with biology is that it is not a physical science resulting in greater challenges in constructing open-ended design challenges. Prior to the CAPSULE program, this teacher’s initial design challenges were more a complementary lab experiment rather than a “design your own experiment”. This teacher’s project to her class involved the design of glow-in-the-dark e-coli that combined bacteria cells with genes from a jellyfish in order to make it luminous. The students were asked to use the EDP to explore, create, and redesign a genetically modified organism (GMO) to achieve the project goal.

Students Using EDP: Students were required to use the steps of EDP to successfully transform an organism, in this case E.coli to change its genetic features. Students researched existing genetically modified organism and their current laboratory methods. Students were also required to understand that multiple solutions can exist. Similarly, they were required to transform an organism through insertion of a plasmid containing the gene of interest. Each group was then required to use the pGLO plasmid to transform the respective E.coli cells. Students then created a prototype that allowed E.coli to glow green when placed under a UV light. In any capstone project, there will be some groups that successfully create a working prototype and others that do not. Unfortunately, for some students, their E.coli did not glow when placed under the UV light. In any prototype situation, however, there are always situations for modifications. For the final step of EDP for this E.coli capstone project, students were required to modify the E.coli transformation by changing either the experimental variables or the test organism itself. Unlike Case Study 1, students had a more restricted capstone experience in biology due to the required materials and the particular unit students were studying. For this set of students, the E.coli cells glowed brightly under the presence of UV light. Figure 3 shows the E.coli cells glow. Figure 3 shows the genetically altered organism from its original form (the non-glowing plates) and the genetically modified organism (the glowing tray).

Figure 3: Glowing E.Coli

Similar to Case Study 1, this class discussed the overall capstone experience. Although they had a very different experience than Zoology, much of the discussion centered around whether the experience helped the students better understand core biology principles of modifying organisms. The students' feedback was primarily based on limited exploration of the overall capstone challenge. Students wished there was more leeway regarding the organisms they could modify. For some students, they desired a more open-ended challenge, while others were comfortable with more direction.

With this particular class, we discussed multiple aspects of how biology and engineering intersect. Many students could not provide examples of career opportunities in biology. Students also did not understand that chemistry and biology affects almost everything they eat and drink. Furthermore, students did not understand that biology has a lot to do with everyday items such as the sneakers they wear and the furniture they sit on. Until biological applications were brought to their attention, students fail to realize that things are designed based on the human body. Engineering-based learning bridges this gap for students in all STEM courses, especially in the life sciences.

7 Conclusion and Implications

This paper presents two examples of classrooms where engineering implementation is difficult due to the nature of the course. However, with teacher creativity, engineering can be integrated in unconventional ways. For example, the Zoology course primarily focused on the biology of animals but their capstone project focused on the design of the animals' habitat, a zoo. Unlike Zoology, the AP Biology course modified premade "Genetically Modified Organisms" kits that allowed students to experience more engineering processes rather than design.

Engineering can have a great impact on K-12 students if integrated and implemented correctly into STEM courses. In order to accomplish that, teachers need the proper training and tools. Like their students, teachers need to have the proper tools and experiences in order to understand the value of engineering in their classrooms. We have created a teaching pedagogy of engineering-based learning where teachers experience what their students would experience. However, teachers need to be willing to try new experiences, reinvent themselves and potentially change their teaching pedagogy to show students STEM theory has a real-world application. Our experience has shown and continues to show that teachers are willing and able to do just that providing exceptional results and enriching rewards for students.

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