Abstract
We worked with Massachusetts Audubon’s Wachusett Meadow wildlife sanctuary and Clinton elementary school to advance engineering skills in current Science, Technology, Engineering and Math (STEM) curricula. Developing engineering skills in early education is beneficial for students to develop the ability to problem solve and learn how to make real world connections. With these developed skills students are able to use them not only in engineering, but in other aspects of education which will help them understand and retain more information, setting them up for better success in the future. In order to improve engineering in Clinton’s STEM curriculum we created design challenges to implement into their curriculum. We tested our design challenges out on Clinton’s 3rd grade class and at a program at Mass. Audubon. We were able to receive data that allowed us to perfect our challenges and improve those challenges for implementation at any school. In order for proper application we created a teacher’s editions of each challenge so educators would feel more comfortable and increase their exposure to engineering materials. We also supplied the teachers with a voice over presentation to ensure that they had access to multiple STEM education resources. With this more advanced engineering curriculum the students will develop skills that will set them up for a brighter future.
Early STEM Education: The Importance of Engineering skills

Science, Technology, Engineering, and Math (STEM) related industries lead the way in scientific advancement. In particular, engineering is the practice of solving problems using broad topics in STEM to push societal elevation. These areas of research allow us to find ways to control diseases, create higher resolution computer monitors, make the internet more accessible, create smarter artificial intelligence, as well as create artificial organs instead of focusing on finding a limited supply of donors. STEM fields continue to grow, and as a result, job availability progressively rises. Therefore, STEM has become an important subject of study in all stages of education, especially at the early elementary levels. If STEM material is not covered early in students’ education they are steered away from scientific and engineering-related futures. As Swift and Watkins put it: “These students need basic concepts and terminology. Later student performance and interest depend on this foundation. Resources and outreach at middle and high school levels may be too late for some students.” Teachers are not as familiar with the engineering and technology aspects of STEM and therefore need help finding ways to get students at young levels introduced to STEM; “Elementary teachers need support to find ways to incorporate more hands-on, inquiry-based activities into the math and science curricula to assist in teaching the more abstract concepts”. Previously President Obama appointed a National STEM Director to broaden a range of STEM initiatives into school’s across the country. In many other countries, such as South Africa, educators are implementing similar initiatives to promote a coalition of SET standards (Science, Engineering and Technology). Initiatives that emphasize science and engineering education prepares students for future workforce needs. Today, students are not prepared for the workforce because they struggle to solve complex problems with multiple solutions. According to Casey Fabris, a reporter from The Chronicle of Higher Education, students feel they are qualified to enter the workforce but employers say otherwise.

While 59 percent of students said they were well prepared to analyze and solve complex problems, just 24 percent of employers said they had found that to be true of recent college graduates.3 The reasoning for this may be because students who intend to go to a four year college feel as though they do not need to start learning on a competitive level until they reach higher education. This cultural phenomenon of students not putting forward their best effort to learn the material and our educators intimidated to teach specific topics because of a lack of experience in subjects such as engineering can potentially put students in today’s world at a disadvantage. Thus resulting in an inconsistency of what the employers want and the level of motivation for the students matched to educators teaching style of not catering to real world applications.

The solution to this problem boils down to teaching STEM effectively. Instructing STEM is different from teaching other topics in terms of what needs to be covered and how to approach the material. The best way to teach STEM includes design challenges that are based on real world problem solving, as well as ensuring the students experience the iterative nature of the engineering design process.4 Children are natural engineers, and by describing their activities as engineering can provide a positive association among the children in terms of their natural design process. This instinctive inclination to understand how things work and how to improve them is in fact the basis of engineering.5 In the process of allowing students to freely explore and evaluate different problems, students can develop individual thoughts. A powerful STEM teaching method involves a hands-on approach to problem solving that gets children working in a group to solve a problem.6 Problem solving will not only get students engaged in STEM programs but also as students are more interested they are more likely to be better prepared for a job in STEM fields.

In comparison to the rest of the United states, Massachusetts excels in its educational performance; if Massachusetts were a country it would rank 9th in math, 4th in reading, and 2nd in science.7 More specifically, compared to the rest of the U.S. Massachusetts is above average in nearly all forms of education and test performance.8 These are impressive statistics for a given state, but the rest of the U.S. remains average in regards to education in Science and Mathematics. Although Massachusetts ranks highly in education, its educators must continue innovating their teaching methods in order to develop cutting-edge approaches to learning that will prepare students for workforce. Also, innovation leadership in Massachusetts has the potential to set a precedent for other states as well. The Massachusetts Board of Elementary and Secondary Education Members describe elementary school years as a critical time to engage students in science and engineering practices where students can later build relations based off of prior or current knowledge in STEM to later education.9 The Board identifies the need to inspire students at a young age, and as a result the current Massachusetts curriculum touches upon the important topics of Earth Studies, Life Science, and Physical Forces.10 These topics are great exploratory steps for students to get a baseline of Science but provide little exposure to...

Figure 1: Kids building a Teepee at Mass Audubon’s Wachusett’s Wildlife sanctuary. (Mass Audubon, 2019)
Engineering aspects of learning. Educators should implement design challenges and in-class activities that would set a blueprint for classroom learning. Specifically, design challenges ought to relate material to real-world problems, prompting the students to develop a solution that must then be iteratively tested. Donna Taylor of the WPI STEM education center suggests that it is important for the students to understand failure and learn from it through a repetitive design process in order to conceptualize real-world application. A hands-on approach to teaching STEM helps prepare students for the workforce in today's classrooms.

Mass Audubon is a non-profit organization that aims to expand conservation efforts across the state. Their Wachusett Meadow Wildlife Sanctuary provides science-related instruction to people of all ages, that directly applies to the nature seen and observed at the sanctuary. Third grade students at Clinton Elementary School take an annual field trip to the sanctuary to work on a design challenge. The goal of the education program at the sanctuary is to get students outside to enjoy nature and learn new thing about their environment. The trip proves to be insufficient for the students, it remains a great opportunity to combine classroom-based learning with applied learning in an integrated curriculum. However, one two-hour field trip is hardly enough time to provide third grade students with a meaningful and informative experience. On the other hand in the classroom students learn about things that they cannot directly apply. The challenge presented is in developing a curriculum that exposes students to the engineering design process while also relating it to the sanctuary and the material covered in the classroom already.

Through this project, we have addressed standing issues by evaluating effective methods of teaching to help students stay interested in learning about STEM while developing engineering skills. The aim of this project was to create an engaging curriculum that prepares students for a field trip, presents STEM material in an engaging way and augments their creative nature into their career and life. We worked to further develop engineering skills by providing thought-inducing design challenges and activities. Due to significant diversity in the way students absorb knowledge we created activities that will expose students to different styles of teaching. We then collected results on what was effective and what was counterproductive. The Wachusett Meadow Wildlife Sanctuary has its own educational programs that are built around hands-on design challenges. While gathering information we incorporated the views of the wildlife sanctuary into the curriculum in terms of how we could get students to understand the roles that animals play in their environment and how they accomplish their goals using an engineering-like thought process. With this understanding the students are then able to apply what they have learned in the classroom to hands-on complex problems throughout the year to inevitably help develop their critical thinking skills and prepare them for a career of real-world problem solving. Our other goal is to Characterize common barriers and identify opportunities to further educate teachers about engineering. The purpose of this is to make teachers more comfortable when approaching engineering education, and in return hopefully they will visit engineering topics more often.

Figure 2: Mass Audubon’s Wachusett’s Wildlife Sanctuary Crocker Farm House. (Mass Audubon, 2019)
Importance of STEM Opportunities

Science, technology, engineering and mathematics (STEM) are extremely prevalent today and are only becoming more influential. From rocket ships to cell phones, defibrillators to roller coasters, STEM advancements are allowing humans to live longer and more fulfilling lives.

There are a plethora of different types of technology involved, from material science for cheaper materials to computer science for self driving cars and even medical studies for airbags. The mix of completely different STEM fields required to compete in industry on an international level demonstrates the necessity for competitive STEM technology in general. To compete with other countries economically, these tools are crucial.

Companies such as Uber have used technology to completely change the transportation industry in an extremely efficient way. Even today, scientists and engineers are capable of growing organs in a lab. This fabrication is a result of medical research, material science, and a strong economy capable of investing the resources necessary to manufacture human organs.

Because of their growing role in developing our country, STEM fields provide more career opportunities than many other occupations. A U.S. Department of Commerce study found that STEM occupations were projected to grow from 2008 to 2018 by 17 percent compared to the 9.8 percent growth of non-STEM occupations. A visual representation of this growth is shown in Figure 3. This study also displays a consistent trend that non-STEM occupations have had higher unemployment rates than that of STEM occupations in Figure 4 from 1994 to 2010. Additionally, STEM occupants earn 26 percent more than non-STEM occupants. People with a STEM background receive higher earnings regardless of whether they work in STEM or non-STEM fields. Essentially, working in STEM fields provides comfortable occupations which often have little chance of becoming obsolete.

Another study done by the U.S. Department of Education supports the claim that STEM occupations will increase dramatically. Figure 5 displays the future opportunities that STEM presents to innovators, educators, and engineers. Some of these occupations are becoming more prevalent in our nation, such as biomedical engineering and medical scientists in healthcare. As the internet continues to grow and evolve with time so do it’s computer system engineers.

A top ten growing professions article lists the fastest growing professions (in order) as: Software Applications Developers, Computer System Analysts, Computer User Support Specialists, Software Systems Developer, Civil Engineers, Computer Programmers,
Salespeople for scientific and technical products, Network and Computer Systems Administrators, Mechanical Engineers and Computer & Information Systems Managers. This specific list can be thought of as most kinds of engineering with a special focus on computer science. Other projections put a greater emphasis on medical fields, but computer and software fields are irrefutable growing.

Surprisingly, these occupations only account for 5.9 percent of the total U.S. workforce and together 15.1 percent of the U.S. professional workforce. STEM fields are crucial to U.S. economic competitiveness. For our country, STEM is key to staying competitive and economically healthy.

With this increase in growth there must be an increase in people who are well educated in STEM disciplines and ready to join the workforce. For students to embrace engineering on a large scale, engineering instruction has to change. One thing to understand is the purpose of engineering and its real world applications.

Best Practices for Teaching STEM/Engineering

While all STEM is important for moving forward technologically, engineering is a keystone field of study. Ultimately while engineering is important, it would be brought to a halt if advancements in the supporting STEM fields discontinued. The greatest minds in STEM have not been noted for their creations, but for their discoveries and theories. For example, Nikola Tesla and Albert Einstein are best known for scientific breakthroughs on which modern engineering still relies. The technology required to make precise measurements often necessary for testing is also a consistently limiting factor in engineering. Engineering is truly the keystone discipline, but like all keystones, it’s meaning is lost without its supporting STEM disciplines.

Science and engineering remain paramount in elementary classrooms. Interestingly, because of their many similarities, students often struggle to differentiate between the two areas of study. While both scientists and engineers deal with very similar issues, their jobs are very different. Engineers focus on implementing current technology while scientists focus on gaining a better understanding of how the world works. In spite of these differences, the common use of one class to cover both disciplines as well as the similar nature of the classes tend to confuse students. Bybee explains the difference as:

The practices of science and engineering overlap in many ways. With the exception of their goals—science proposes questions about the natural world and proposes answers in the form of evidence-based explanations, and engineering identifies problems of human needs and aspirations and proposes solutions in the form of new products and processes—science and engineering practices are parallel and complementary.

In early elementary levels data collection methods for science and engineering seem to be identical; “Both science and engineering involve the analysis and interpretation of data. In lower grades, students simply record and share observations through drawings, writing, whole numbers, and oral reports.” From a teaching standpoint, the two areas of study are so related they are often taught in the same classroom, especially in lower grade levels. The relationship between the areas of study are parallel and complementary; the relationship is parallel because each area relies on each other and thus are associated with all the same things, and complementary because engineering makes practical use of science discoveries about the physical world.

The Engineering Design Process fundamentally guides engineering practice and teaching. The Engineering Design Process is a series of steps in which a person can solve problems through a series of questions and outcomes. This system is designed so that in the development of creating a solution for the identified issue, the engineer can repeat any steps as many times as needed to achieve the ultimate goal. The Engineering Design Process was intended for the engineer to make improvements along the way and learn from failure to expand the scope of the final product. Application of the Engineering Design Process is a critical aspect of engineering. Many steps of the cycle focus on the non-design aspects of engineering such as background research and evaluation which is important to establishing an interdisciplinary connection to other aspects.
of the engineering process. Lastly, the cycle demonstrates that the product can always be improved. The reiterative nature of the cycle demonstrates the sometimes grueling process of developing a truly finished product. Upon speaking to Donna Taylor from the WPI STEM Education Center, she added that it is “Important for students to experience failure”. This experience is important because it allows the students to reflect on their product and wonder why the end result did not reflect what they hypothesized. Therefore, the challenge the teacher presents to the student must allow for the possibility of the student having to redesign and in turn once again go through the steps of the Engineering Design Process. Training the brain to think like an engineer will prepare these students for real world problems when they enter adulthood.

When using the Engineering Design Process, students are often analyzing and evaluating an issue. This methodology increasingly develops as students use critical thinking to solve complex problems. Donna Taylor from the WPI STEM Education Center emphasized the importance of critical thinking at an early age; these skills are crucial in a student's preparation for real world problems. Beyond emphasizing the importance of critical thinking, Donna and many other educators are modifying exercises which catalyze critical thinking among students. At such a young age, their imagination and creativity are often still developing. Nature activities develop a deeper understanding for our ecosystem and allow students to develop critical thinking skills. Nature is an excellent setting for young students to tap into evaluation and engineering skills. For example: what makes a certain part of an animal useful, what is the purpose this structure serves, and how would humans mimic these structures for the benefit of our world? By simply going through this thought process, these students are analyzing, evaluating, and relating the strengths of certain animals. Later when reflecting upon how engineers can come up with designing inventions based off of animal characteristics, students develop an understanding of what works and what doesn’t work. Students can then apply these skills to reference a unique structure in nature that they have seen and brainstorm corresponding inventions to help the world. 

![Figure 6: Engineering Design Process.](image-url)
The United States is Falling Behind in STEM Education

Despite the evident importance of STEM competitiveness for a country, the United States is falling behind. The U.S. spends more money on education than most developed countries and yet our test scores are about average. The United States spends $15,171 per student while the international average spent is around $9,313. As seen in Figure 7a below, the United States is behind in science and mathematics especially when outliers are ignored. Mexico, for example is in approximately the bottom quarter but only spends $2,993 per student. When countries with similar educational budget are compared, the U.S. falls further down the list.

In Figure 7b science scores are on the left and mathematics scores are on the right. As you can see the U.S. is slightly above the international average for science and below the average in mathematics. With such a concern for STEM, money does not seem to be the issue; it has something to do with our teaching style and culture. As teachers educate students in any grade level, they cover individual topics of Science, Mathematics, and English; but they do not bridge these subjects together for the overall hierarchy of better understanding. This barrier for students learning real world applications is due to educators.

Elementary School teachers often feel uncomfortable teaching these ideas because they stretch the realm of what they were taught. For students future success, we must teach our educators how these individual subjects coexist with one another to build the foundation of learning before we teach the future minds of our world. To ensure that students are exposed to beneficial STEM instruction, the material must follow certain guidelines.

Quality STEM Framework

The best way to teach STEM is to present problems requiring investigation. The STEM education quality framework is built from ten components that lay a path for students to fully grasp engineering qualities helping them completely evaluate problems. It’s purpose is to provide a means to measure the quality of STEM material taught in the classroom. The framework is a useful guide to follow when developing activities/exercises. The quality components are: potential for engaging students of diverse academic backgrounds, degree of STEM integration, connections to non-STEM disciplines, integrity of the academic content, quality of the cognitive task, connections to STEM careers, individual accountability in a collaborative culture, a rubric based assessment system, application of the engineering design process, and quality of technology integration. All of these elements help students better understand STEM and utilize problem solving approaches in everyday activities, making them important to include in all STEM material presented to the students.

One point to focus on specifically is the first element, having potential for engaging students of diverse academic backgrounds. Quality STEM instruction requires a large amount of knowledge and skills directly from Science, Technology, Engineering and Mathematics. While focusing on STEM related topics is important, it is worth noting that making connections to non-STEM disciplines is also beneficial. Educators in STEM classrooms often have their students write out experiments in the form of a lab report or simply include a reflection piece of the work they have done. This can often be tying the outcomes they have gained from the exercise to other lesson plan elements.

Figure 7a: U.S. science, math, and reading scores compared to other countries. Figure 7b: How the U.S. stacks up internationally in regards to science and math respectively.
Methodology in Developing a Curriculum

Our two objectives for this project have been satisfied by our methods with persistent effort towards conducting research into education. We value the importance of what our sponsor and the educators at Clinton Elementary School want. Multiple interviews, tours of the Mass Audubon Wachusett Meadow Wildlife Sanctuary, attending staff meetings, and having a better understanding of how a third-grade classroom is conducted were essential to making the current curriculum more inclusive.

The expansion of engineering in a STEM curriculum that will prepare students for the end of the year field trip at Mass Audubon’s Wachusett Meadow Wildlife Sanctuary.

We achieved this objective by doing background research into ways students stay engaged and how to effectively expand engineering topics upon what is already taught in elementary classrooms. Prior to implementing our engineering activities into the third-grade classroom, we took part in a focus group with the Clinton Elementary third-grade staff to better understand how third-grade classrooms are conducted; their specific concerns and suggestions for us to tailor our specific exercises to the current curriculum; and to show them one of the many design challenges that we would provide them. We chose to use a focus group when collaborating with the school teachers because we believed focus groups are cited as being a quick way to gather a lot of feedback during an exploratory phase of research. They are also helpful in gauging how popular different ideas are because the group will brainstorm together. Based on the educators’ insights, our team made small revisions to our material, creating an effective draft of a curriculum prior to testing some of the activities.

Following this focus group, we received the lesson plans the educators are required to teach based on the state of Massachusetts curriculum guidelines. Our mission of implementing different activities large or small can go a long way for the students to gain a better understanding of the material by accommodating different types of learners. These activities vary in duration to increase the range in which teachers can apply our activities when lesson planning. The students currently participate in design challenges, however they don’t necessarily follow the engineering design process. Therefore, our focus was to create new challenges while taking into consideration current challenges that will need to be revisited for the students to understand how to utilize the engineering design process for greater value. Once we knew where the teachers needed help we then suggested different activities for inclusion in their current curriculum.

To evaluate the effectiveness of our proposed curriculum we tested two of our activities at Clinton Elementary School and Wachusett Meadow Wildlife Sanctuary. Clinton Elementary had seven third-grade classrooms to present an activity to approximately 140 students. While Wachusett Meadow Wildlife Sanctuary had a small group of fifteen students where we presented a different activity. We understand that because we have not taught a classroom setting before, the activities were not necessarily perfectly instructed by each member of our group. In addition to receiving feedback from the educators, we will evaluate the students through participant observation on their use of time, engagement, and level of understanding of the activity. The use of participant observation allowed us to analyze how these students react to kinesthetic activities, follow a list of instructions, and explore solutions to a problem statement. The collection of the students worksheets for the activities and analysis of our participant observations sheets provides us a great deal of information to make final revisions to our activities to best suit these classrooms and learning environments.

In order to achieve our goal of tying our curriculum into Wachusett Meadow Wildlife Sanctuary, we visited Wachusett Meadow Wildlife Sanctuary four times to see how field trips are conducted. This gave us insight into the staff’s teaching style and viewing the locations in which the coordinators of the Sanctuary bring the Clinton students to do their design challenges.

Characterizing common barriers and identifying opportunities to further educate teachers about engineering.

We achieved this objective by completing a comprehensive literature review and then creating a presentation for elementary teachers to provide a foundation for teaching engineering. First we determined critical topics of engineering for elementary educators. These include the engineering design process and the Quality STEM Education Framework. We conducted several semi-structured interviews with primary educators from different schools to gauge the amount of exposure educators get to engineering. These sources include Kathy Chalupka, an Auburn Elementary educator; Carolyn Bressette, an East Brookfield Elementary educator; and Andrew Wood, a previous elementary teacher who has previously taught in the Newton Elementary School system and is now a primary educator in town, Vermont with a background in STEAM education.

Through these interviews with educators, we extrapolated that an effective way to increase basic exposure would be to give a brief introduction to engineering and the best practices of how to incorporate engineering into elementary school classrooms in the form of presentation slides. Presentation slides as a deliverable allow educators to share the information along internally or to other school systems in the form of presentation notes and visuals after the duration of our IQP. The teachers can look at these presentation slides as a reminder of how to get the most comprehensive understanding from the students by utilizing certain aspects of learning. Our central message is that engineering instruction differs from that of other subjects, in the way that it is fundamentally guided by the engineering design process.

“It is important for student to experience failure.”
– Donna Taylor
Figure 8: Methodology outline.

- Developing Engineering in STEM Education
  - Expansion of Engineering Materials
    - Participant Observation
  - Increasing Educator’s Exposure to Engineering
    - Focus Groups
    - Semi-Structured Interviews
    - Literature Review
Objective one: Implementation of Supplementary Materials

The Quality STEM Education Framework\(^\text{19}\) guided the development of our expanded curriculum. Our curriculum has a strong focus on the engineering design process and design challenges to achieve our first objective. The Quality STEM Education Framework stood as a template for designing activities for the students to engage in cognitively and academically challenging material with a strong connection to STEM careers. While it has implications on a large scale, it holds relevance for small scale design initiatives for, “at the micro-level, the framework and rubrics can guide teachers in designing quality STEM learning experiences and provide a valuable tool for reflection and self-assessment.”\(^\text{19}\)

A major benefit in our use of this Quality STEM Education Framework is the fact that it provides a concrete foundation for all STEM discussion to spring from. It may “serve as the common ground where both teachers and STEM professionals can anchor their collaborative work as they endeavor to build the bridges from classrooms to STEM careers.”\(^\text{19}\) We wanted to ensure that our work could be presented and discussed by educators of different backgrounds and this specific framework allowed for us to do that.

A major part of the Quality STEM Education Framework is the engineering design process. In any STEM field, experiencing failure is pivotal for students; without failure, students would not be able to develop evaluation skills to redesign a product to make it better. An effective way to train students to apply the engineering design process is integrating hands-on design challenges into their STEM curriculum. Currently, Clinton Elementary relies heavily on Mystery Science Videos to demonstrate most science lessons. At the end of each week, students complete a wide range of Mystery Science activities linking to their videos. A highly credible educator with many years of experience in elementary and primary education stated that Mystery Science was a good start for introducing science topics and hands-on activities in Clinton. Kids love mystery science videos, but the lessons are unconnected to the rest of the day’s lesson plan.\(^\text{20}\) Elementary students learn over time and one day lessons do not build a solid foundation of meaningful learning. Andrew Wood commented that Mystery Science is “fun and isolated.”\(^\text{20}\) Clinton Elementary

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<tr>
<th>#</th>
<th>Components</th>
<th>Descriptions</th>
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<tr>
<td>1</td>
<td>Potential for Student Engagement</td>
<td>Quality STEM learning experiences are designed to engage the minds and imaginations of students of diverse academic backgrounds.</td>
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<td>2</td>
<td>Degree of STEM Integration</td>
<td>Quality STEM learning experiences are carefully designed to help students integrate knowledge and skills from Science, Technology, Engineering and Mathematics.</td>
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<td>3</td>
<td>Connections to Non-STEM Disciplines</td>
<td>Quality STEM learning experiences help students connect STEM knowledge and skills with academic standards from other disciplines.</td>
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<td>4</td>
<td>Integrity of the Academic Content</td>
<td>Quality STEM learning experiences are content-accurate, anchored to the relevant content standards, and focused on the big ideas and foundational skills critical to future learning in the targeted discipline(s).</td>
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<td>5</td>
<td>Quality of the Cognitive Task</td>
<td>Quality STEM learning experiences challenge students to develop higher order thinking skills through processes such as inquiry, problem-solving, and creative thinking.</td>
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<td>6</td>
<td>Connections to STEM Careers</td>
<td>Quality STEM learning experiences place students in learning environments that help them to better understand and personally consider STEM careers.</td>
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<td>7</td>
<td>Individual Accountability in a Collaborative Culture</td>
<td>Quality STEM learning experiences often require students to work and learn independently and in collaboration with others using effective interpersonal skills.</td>
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<td>8</td>
<td>Nature of Assessment(s)</td>
<td>Quality STEM learning experiences require students to demonstrate knowledge and skill, in part, through performance-based tasks.</td>
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<td>9</td>
<td>Application of the Engineering Design Process</td>
<td>Quality STEM learning experiences require students to demonstrate knowledge and skills fundamental to the engineering design process (e.g., brainstorming, researching, creating, testing, improving, etc.).</td>
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<td>10</td>
<td>Quality of Technology Integration</td>
<td>Quality STEM learning experiences provide students with hands-on experience in using multiple technologies. (Examples: computer hardware and software, calculators, probes, scales, microscopes, rulers and hand lenses to name just a few)</td>
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Figure 9: List of Components in the Quality STEM Education Framework.\(^\text{19}\)
Curriculum Development Based on Engineering Design Principle

Our mission was to make the current STEM curriculum more effective through the implementation of supplemental design challenges. We created nine activities that we proposed would help develop Quality STEM Education in Clinton Elementary School. These exercises directly correlate to topics covered in Clinton’s current curriculum. Initially, we employed the STE Framework Worksheet to ensure that we understood the standard of the topic lesson. This involved breaking down Massachusetts standards into what we are asking the students to do, specifically the core idea and the vocabulary, and the outcomes we would like our students to take away. Each activity utilized the engineering design process. The steps to this process include: identify a problem, hypothesize or create a design to solve that problem, test your design or experiment, and then describe your outcomes, reflect on how you could effectively done the experiment better, or how can we take this knowledge and advance the world.

Direct Testing at Clinton Elementary

After introducing our proposed Three Little Pigs activity, we taught a class about static electricity, as the students at Clinton were learning about magnets and invisible forces and thus the balloon activity was born and ready to be tested. Based off of the constructive feedback that the teachers gave us on the Three Little Pigs example as well as our project sponsor, we made this activity much simpler and assigned each student in a group to a particular item.

Development Based on Needs of Clinton Elementary

We met with the third grade educators from Clinton Elementary before creating specific exercises in order to better understand their current teaching methods/schedule and evaluate one of our prototyped Three Little Pigs design challenges. During a focus group we discovered that Clinton Elementary School almost exclusively uses Mystery Science for science related instruction. The teachers spend thirty minutes per day teaching science, and the majority of this time is spent watching Mystery Science videos. Additionally, we presented our Three Little Pigs activity. The teachers seemed to gravitate toward this activity; they were very enthusiastic and reassured our group that the students would love a childhood story come to life. Teachers saw the potential of this activity; it utilized a basic material analysis while also incorporating the engineering design process. A material analysis is a process that engineers use to determine the best material for a certain application. Engineers often test different prototypes made from different materials. Students would have to work in groups and make homes for the pigs to be protected from the Big Bad Wolf. Originally we had the activity set up where each table had all the materials in front of the students. While this seemed like a great idea, the Clinton elementary school teachers made it clear to us that students would be distracted by all of the materials at once. Overall we had very positive feedback from the teachers on our proposed activity and were very excited to have our group come in their classrooms and work with the kids. They offered one critique that our activity seemed a bit too complex for the students; in response to this feedback we them attempted to simplify all of our activities in our subsequent iteration of our design challenges.

Figure 10: Worksheet created for a Static Electricity lesson.
We handed out each item to that particular student, but did not hand out the balloon to each group until the students hypothesized what item the balloon could pick up. The reasoning behind this is that students were very excited to use the balloons and by giving them to the students immediately, they would be easily distracted and would not listen to directions. The balloons could be seen as a positive reinforcement for their efforts of following directions to then proceed with the activity. Our group taught this exercise in seven different classrooms. Each person in the group taught at least one class in conjunction with the teacher. With the student groups, being assigned individual object improved cooperation within the groups only if there was the same number of materials as students. Some groups had either three or five students; the groups of three struggled to share the extra item and the groups of five struggled to stay focused as a because a few students could do very little. One of the WPI instructors experimented with choosing a group leader for two of the seven activities; this encouraged one student to be particularly invested in filling out the worksheet and kept the rest of the teammates on track. Preparation played a huge part in deciding the amount of material covered in the activity. In the classes where the students were already separated into the necessary groups it was much faster to get right into the activity. In two of the seven classrooms, desks were not broken up into manageable groups. This logistical problem limited the amount of material covered and forced us to reevaluate the duration of our design activity for the planned curriculum. In the classrooms where the teachers did not prepare for the activity ahead of time or the students were not broken up into groups, the WPI student instructors finished promptly at thirty minutes. In other classrooms with teachers who were well prepared to teach the activity, the WPI student instructors added another portion to the activity to ensure it lasted a full 30 minutes. Two of us had the students apply what they had learned while sitting at their desk and critically thinking about what else might possibly get picked up by the balloon. After thinking about what would work they then had to test it. While one other instructor asked students to explain why they made their observations of items being able to stick or not stick to the balloon prior to showing them the end of lesson video. Afterwards the students were asked to reflect on what they had learned. Most of the students had a basic understanding of what the balloon would pick up and what it wouldn’t based off of the collected worksheets. The students were able to correctly identify that static electricity was the reason that the paper was picked up. In addition to the feedback we received from the students and teachers from Clinton Elementary, we sought constructive feedback from our sponsor and representative from Mass Audubon, Kristin Steinmetz. We presented all our design challenges in a focus group where she gave us specific details on each design challenge. She recommended that we include a wrap up explanation on the teacher edition for every activity, as well as any possible connections to the wildlife sanctuary. When listening to her constructive feedback we saw room for improvement when educating students on local animals and nature engineers in our activities and therefore added additional information correspondingly.

**Figure 11:** Clintons third grade students testing a static electricity lesson. (Clinton elementary, 2019)

**Direct Testing at Wachusett Meadow Wildlife Sanctuary**

To better understand Wachusett Meadow Wildlife Sanctuary we made multiple trips to their location in Princeton to understand the details of their field trip and how they conduct educational programs. In her strong efforts Kristin attempted to incorporate engineering aspects in the field trip design challenge. Kristin stated to us that she enjoyed the students playing in nature but did not know if her current design challenges involved engineering aspects. She ventured out of her comfort zone with these challenge to teach engineering with no previous exposure and in turn provided an opportunity for WPI students to step in and together help create a more effective program. After our team viewed the locations where students from Clinton Elementary visit during their field trip we were able to alter the initial design challenge that Kristin had previously come up with based on the natural resources available. One of our deliverables for Wachusett Meadow Wildlife Sanctuary was creating a plausible list of design challenges that Kristin and the Clinton teaching staff can use based on their description for the end of the year field trip. These design challenges correlate directly to challenges the students will be engaged with in the year long newly reform Clinton Elementary curriculum. We suggested that the students still remain using materials they find on the ground to build various structures to help different animals survive. An example of this could be a shelter for an animal to live in or a stand for a bird to build their nest on to keep it more protected. Ultimately we left it up to the students to decide what they were going to build and how they were going to impact the local animals.

After our multiple visits to Wachusett Meadow Wildlife Sanctuary including the educational classroom exercise of “Do Insects Freeze in Winter?” and the tour involved, we felt comfortable teaching one of our design activities with the attending students. Mass Audubon works a lot with home schooled children as well students of all ages. In order to test our activity we had to ensure that it could be completed by children ages 5-11. This specific activity was developed because Wachusett Meadow educates the students about the local food chain. The activity we chose included: identifying one of the provided predator or prey listed, noting their structural functions.
(strengths and weaknesses), and then illustrating a way to improve this specific animal. We were given a group of fifteen students for the duration of forty-five minutes. This activity is short and simple because several children were much younger than our third grade target age, therefore we gave the students twenty-five minutes to brainstorm and illustrate their animals. This time frame allowed for the students to be creative and establish an illustration that they can be proud of to bring home. While they were doing this our team monitored the students thought process and illustrations. Prior to leaving, we scanned each students worksheet for later evaluation on how the students performed so that the students can bring their worksheet home. Our findings supported that the activity was not too complex for the students. The children were already very knowledgeable in areas of nature, specifically bears. The prior day to our activity the students spent time learning about bear habits, where they live, and what they eat. When we were presenting to the students animals such as bears, they were able to brainstorm together to list factual information of that predator. One nine-year-old student correctly identified that bears are omnivores and that mother grizzly bears indeed eat mostly grass. Another great example of student recognition to animal traits were that

Figure 12: Ideal response for the animal redesign activity done by a student at the Wachusett Wildlife Sanctuary.

Figure 13: Pragmatic response for the animal redesign activity done by a student at the Wachusett Wildlife Sanctuary.
coyotes are great hunters because they were fast and could hunt for long durations. To better understand this students process of thinking, one of the team members asked this student “why do you think this is true?” The student responded that it is because of the coyotes leg strength. This is a vague answer. By asking follow up questions for this students reasoning, it presents the idea to the rest of the class allowing them to question if the student was correct or not. We noticed that the majority of the students were immediately able to identify which animals were predators and which were prey. Younger students seemed to be more eager to participate while older students made thorough more descriptive answers to our questions. The younger students were able to draw basic examples and come up with very simple changes to the animals. These included: pads on coyote feet for improved stealth, as well as larger claws on the bear to increase their digging effectiveness. The older students came up with some very interesting adaptations that showed the students understanding the material, including: increased regenerative abilities, as well as a venomous bite. One thing we had to address was the limitations of adaptations that could be used in the activity. Some of the students added human made appendages and technologies to the animals that were not pertinent to the activity. We added a section in the teacher edition of this worksheet to ensure that the teacher mentions that all adaptations should come from nature.

Our major takeaway from this objective is the ease of brainstorming activities for third grade students to develop engineering skills. As engineering students we were able to discuss ideas for a few hours and come up with 15-20 possible design challenges. The real challenge was in the testing of the curriculum to ensure that it would be effective. We were very limited in our development time, and it was easy for us to come up with ideas that weren’t tested. The holdup on our project was gauging the effectiveness of the activities that we created. However, if this process were to be followed by educators on a large scale they could test their developed activities every year.

Objective Two: Developing Engineering in STEM Education

Other than creating a curriculum, our team set out to develop engineering in STEM education by characterizing common barriers and identifying opportunities to further educate teachers in engineering. The paragraphs below detail the findings of our team’s research and the results of our actions. We share our understanding of the barriers facing elementary school educators from an elementary school teacher’s perspective and identify opportunities to overcome these barriers. To facilitate the incorporation of engineering into STEM curricula, we explain why we endorse a supportive school culture. Then, to proliferate model engineering cultures, we introduce a slideshow presentation we designed to promote STEM education no matter how involved you are in either STEM or education. Finally, my team and I introduce opportunities for research and action outside the scope of our project.

We learned that barriers on all levels hinder engineering in STEM; while the scope of our project focuses on a base level perspective, high level impediments can trickle all the way down to the teacher in a classroom. Different Levels. Internationally, the United States gets less of a “bang for their buck” than most other countries. On the federal level, The Department of Education works with state education departments to maintain a relevant curriculum framework. On the state level, standardized tests limit schools lesson plans to a statewide curriculum plan. Schools can teach their own material, but usually focus on teaching tested material because if the schools scores are too low, the state can restructure the school; something nobody at the school wants. Within the school, the administration is budgeted for daily activity. Administrators are already extremely busy with just their normal job, even if they are not worried about standardized test scores, incorporating STEM just doesn’t seem feasible. Teachers often echo this apprehension. The scope of our project focused on the teachers perspective, but problems manifest themselves in ground level difficulties.

On an individual level, especially for teachers without engineering experience, incorporating new, scary STEM education is a daunting prospect. Andrew Wood, an 4th and 5th grade science teacher in Brownsville VT explains: “students may be difficult to control, loud and noisy, with materials everywhere; therefore it would be overwhelming for them.” Many educators find this chaotic atmosphere extremely off putting. Additionally, third grade teachers generally attend school for education and have little academic background in engineering. As a matter of fact, none of the teachers we interviewed had any academic background in engineering whatsoever, a common predicament in lower school education. This background discrepancy renders teachers particularly averse to engineering incorporation in STEM education. Wood explains: “People spend a lot of time getting the resistors to join the movement... teachers may be against this new style of teaching.” In addition to individual teacher challenges,
structural challenges on a school and state level make engineering incorporation particularly difficult. For administrators, governmental regulation and mandates pressure schools to focus on standardized test scores; this pressure prompts administrators to send teachers scrambling to meet state standards while it denies educators the latitude to incorporate engineering into STEM education. Even though there might be some problems implementing STEM in the beginning, giving educators funds and freedom to try new approaches with STEM education. Professional leeway can incubate proactive growth, but external pressures yield reactionary measures which distract administrators from development. Andrew Wood highlights this lack of administrative support through his contrasting experiences teaching in Brownsville, VT and Newton MA. In Brownsville, a principal supportive of engineering further develops STEM curricula; in Newton, hands-off principals and administrators change frequently and leave forward thinking educators like Wood wondering if they are working at the right school. Unstable administration and distracted principals are indicative of imminent school pressures which cultivate a reactionary approach to education. In contrast, Wood explains how proactive cultures like those in Brownsville capitalize on opportunities for improvement. Wood illustrates a STEM friendly environment where administrators encourage STEM by hiring part-time STEM teachers, admitting contemporary teaching styles, and to paraphrase Wood, giving him money when he asks.

The essential difference between Newton and Brownsville STEM education is cultural; Brownsville grapples with STEM education as a worthwhile endeavor while Newton educators assume a more conservative role in education. On an individual and administrative level, educators in Brownsville are more willing to incorporate engineering into STEM. This administrative willingness to incorporate engineering attracts like-minded educators and further fortifies a STEM bastion. Perhaps the best example of this impetus is Wood’s own personal story of becoming an engineer. Despite the fact that he had no formal engineering education or professional development, Wood identified the importance of engineering education and taught himself enough engineering to teach 4th and 5th graders. Initially, Wood enjoyed the hands-on aspect of engineering and as he taught, became more comfortable with the material as well. Wood joined and leveraged a supportive school culture to overcome engineering implementation problems on an individual level. His is a story that highlights the triumph of goal-oriented initiative over inexperience on the individual and administrative level.

Another inspiring educator at Wachusett Sanctuary demonstrated dauntless gumption when actualizing engineering despite significant challenges. In an underfunded classroom with just a few children from kindergarten to 7th grade, a teacher with little background knowledge of engineering dared to incorporate engineering into a lesson. She began by teaching standard insect lessons, giving a science-focused worksheet and showing off her insect collection; a standard lesson plan which does not include engineering. Then, seamlessly, the instructor began asking students about how they might redesign a bug, keeping in mind the lessons they learned in the previous exercise. The students were given different head, abdominal and leg pictures for insects and then had time to cut, mix and match, paste and color their very own insect. Afterwards, the instructor took the children outside and spent the remainder of the lesson researching indigenous insect populations.

Despite the lack of scale and glamor, her lesson embodies the essence of innovation in engineering education. Taught with enthusiasm, the lesson encouraged creativity; the mix and match aspect teaches students another fundamental engineering principle: there can be...
more than one answer, a fundamental engineering principle. By adding an artistic aspect, students received exposure to more than just one topic. Most importantly, the instructor shared an inquisitive enthusiasm with the students. Innovation is a tedious, awkward battle, fraught with failure, and educational innovation is no different. Forward thinkers like those in Brownsville and Mass Audubon’s Wachusett Sanctuary are models for widespread STEM exposure. To propagate engineering cultures like those found in Brownsville and Wachusett, our team developed a motivational and directive presentation for educators. The presentation begins by showing teachers how engineering, and STEM education can be found in all aspects of education and even their daily life, concluding that educators are already engineers and just don’t know it. We then define the Quality STEM Education Framework in a notably accessible way, with a particular emphasis on engineering’s practical nature. Because we frame engineering as a general way of thinking, we conclude with the bold but well supported claim: STEM is a philosophy.

The presentation uses examples found in research to addresses common teacher barriers. To demonstrate the universal relatability of engineering on a ground level, our presentation showcases a basic engineering challenge for elementary school students. By contrasting technically intimidating definitions with a scholastically benign lesson plan, our first few slides promptly introduce the commonly misconceived breadth of engineering. To demonstrate universal relatability of engineering on the college level, the presentation explores The WPI Plan, a notably successful plan for university wide implementation of engineering. Because of the many non-engineering majors, WPI demonstrates the usefulness of an engineering mindset for everybody, engineer or not. Our final slide is a call to action. The presentation reiterates the universality of STEM culture and urges viewers to embrace engineering education in any capacity possible.

While the presentation targets elementary educators specifically, everybody should learn the basics of STEM. As with many things in life, a full community effort can help make virtually anything happen; STEM education is no exception. Ultimately, people learn from their communities; these communities can be anything, friends, coworkers, schools, towns, cities, nations and even a global community. Our presentation’s focus on all people builds STEM culture amongst friends, schools and nations; in doing so, we will use STEM to change the world.

Conclusion

This project aimed to implement and instruct effective engineering practices in elementary education. Toward this end we provided supplementary materials that will further develop engineering skills in young students. First, we provided a series of example design challenges that integrate well into the overall STEM curriculum for Clinton Elementary School, which is working in partnership with Mass Audubon. We created nine engineering activities and sought feedback from multiple sources through teaching at Clinton Elementary, Mass Audubon’s Wachusett Wildlife Sanctuary, the WPI STEM Center, and three additional educators from elementary backgrounds. These educators expressed enthusiasm in our project because the students simply enjoy being hands on and engaging in age appropriate activities. More importantly, educators noticed a significant need for implementing engineering activities to prepare their students for later education and workforce needs.

Second, we created materials designed to inform educators about the best practices for how to teach engineering. These materials highlighted the fact that engineering cannot be taught in the same ways as math or reading because, it remains fundamentally different from other STEM disciplines. Math and reading can be taught through memorization or repetition in lecture style environments, whereas engineering should be taught through experience and exploration to obtain necessary understanding. Teaching engineering requires the use of the engineering design process. The engineering design process not only provides students with advanced problem solving skills but it teaches students the importance of the failure. Teaching students to learn from failure allows for a better outcome that is not only more precise but requires them to use higher-level problem solving skills. These experiences over time will be beneficial when transferring the knowledge and understanding they have learned over time to real world situations.

For teachers to educate students effectively about the engineering design process they must have an understanding of it themselves. There is a negative connotation that engineering activities require high level math and college education associated with engineering in the minds of elementary educators which holds them back. This association with engineering should be completely dispelled. At a basic level in elementary education, teachers can utilize the engineering design process by asking questions such as: what makes a certain part of an animal useful, what is the purpose this structure serves, and how would humans mimic these structures for the benefit of our world? Asking these questions may be simple, but it forces students to first identify an entity or problem. Secondly, they must do research on that animal and imagine solutions. Finally, after evaluating the finished product and building an understanding of functionality, students can transpose important pieces of information to our world. Thus by developing a design-oriented mindset around themes that are already taught in classrooms, teachers may easily incorporate engineering into elementary education.

Our research focused mainly on elementary school educators in the Worcester area and our supplemental materials enhance the current curriculum in Massachusetts. In the end, our deliverable will influence the teachers on how and why they teach STEM, but more specifically the importance of developing engineering skills. Therefore the scope of our project did not examine: statewide curriculum, grants and financial support for schools, national initiatives and changes in standardized tests. Further research could explore the least intimidating ways to present STEM and engineering to educators.

The U.S. is falling behind on an international level as indicated previously. We suggest the culture and teaching style have to change as opposed to just increasing educational spending. However, we do not directly address what other countries are doing well that causes them to outperform the U.S. This still remains a larger question that needs to be addressed not only in Clinton but all of the United States. The main focus of our project is to demonstrate the importance of STEM in our economic competitiveness and the need for introducing engineering principles in early education. A possible avenue for future research to shed some light on economic competitiveness is into how the government should take action on a federal level and specific reforms that would be necessary to get the U.S. back on track.

Our supplemental activities are developed around Massachusetts state standards; we did not address a need for the state standards to change. We worked to adapt lessons that Clinton Elementary currently uses and ensure that our designed activities satisfy state standards. We treated the state standards as a constraint to work around and it influenced our project accordingly. We also didn’t advocate
The Three Little Pigs

Purpose of activity: Students develop engineering skills through the engineering design process.

How it works:
1. There will be three stations in the room with three designated specially catered to the houses: straw (actual straw), sticks (popsicle sticks), bricks (index cards). Prep each station before the students walk in.
2. Each station will have two groups of students. There will be no more than 4 students per group.
3. Students must first make a hypothesis on what material will be the strongest.
4. Do the activity. Time manage for students to cycle between work areas.
5. Testing will be done by a student from the other group that is the same station. This student will represent the Big Bad Wolf to blow one original straw.
6. Students have 10 minutes to build. After students have done all their testing, students have to reflect upon which material typically uses the strongest and how they would make their structures better based on testing others using the same materials.

Rules:
1. All houses must have a roof.
2. Houses must contain an item that represents the "Little Pig." One is approximate to a tennis ball size.
3. All houses must be a free standing structure and not leaning on a wall.

Additional materials to use:
- Tape
- Small rubber bands
- Elmer's glue
- Ruler
- Scissors

Texting:
For this activity we want the children to think about which material would work best for the situation and then work on their ability to make a structure that would stand on its own and be able to resist "wind force."

If:
If building and testing takes too long then break the building and testing into two classroom days. First day have the students build their structures and groups and still have the groups rotate. The following day, have the students stay in their same groups and test at each station. After, have the students reflect on what they have learned about materials and how they would make it better using the same materials.

Connection to Wachusetts Meadow Wildlife Sanctuary:
One of the design challenges the students will be doing on the field trip is creating a structure using natural resources they find off of the ground. This often is sticks. This activity will help them visualize how to build effective structures.
for a change in policy in terms of MCAS testing; Massachusetts does not test the comprehension of science at the third grade level. Issues surround teaching towards the test for mathematics and English language arts because the schools will typically spend more time in these subjects rather than equal time in the science department. This is a key issue for further researchers to investigate equal learning opportunities in all subjects to create a more well-rounded student. Standardized testing and Massachusetts state standards stood as a task too large for a group of four students to conquer in a short duration while building an engineering curriculum that educates students and teachers. Possible matters to look into include the No Child Left Behind Law. This law covers but is not limited to household instability, ethnic diversity, and child neglect; it would provide proper identity of all constraints affecting student learning.

In terms of school administrations and how they deal with STEM integration, we had very limited interaction over the course of our project. Dealing with schools can be difficult and communication is not always consistent; given their busy class schedules and the fact that they are dealing with other outside representatives. Our project scope did not include evaluating the principals’ best use of resources for teaching STEM and integrating engineering skills on a widespread scale. This being said, Clinton Elementary administration gave us a copy of their current third grade science curriculum. Unfortunately we were not able to obtain a copy of any specific design challenges that the students work on in the STEM room every seven days. Because of this we were not able to alter any of their current design challenge to make them more effective or engaging. In creating design challenges we were limited to the topics that are covered in the current curriculum that their administration passed onto us. We used their lesson plans to pick and choose places to integrate our own activities. These activities tied into what the students were already learning and are meant to be supplemental to the material presented by the teachers.

Our objectives for this project have been satisfied by our methods with persistent effort towards conducting research into education. We value the importance of what our sponsor and the educators at Clinton Elementary School want. Multiple interviews, tours of the Mass Audubon’s Wachusett Meadow Wildlife Sanctuary, as well as having a better understanding of how a third-grade classroom is conducted were essential to making the current curriculum more inclusive. In our final deliverable, we made student and teacher versions of each design activity and added them to a zip file, created plausible activities for the students to do at the end of the year field trip, and a presentation educating the Clinton Elementary staff about engineering on an elementary level. We will distribute these supplementary materials to Clinton Elementary as well as our sponsor representative from Mass Audubon. They will be used to entice other schools in the local area to incorporate our design activities that build up towards a field trip to Mass Audubon’s Wachusett Meadow Wildlife Sanctuary.

References


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