Capstone Courses in Middle School
(Work in Progress)

Engineering is slowly making its way into K-12 education. Although there have been some notable advances like the inclusion of engineering processes in the Next Generation Science Standards (NGSS) [1], currently the options for engineering education are still limited and few. Nevertheless, one recent innovation in some K-12 schools seems to have a great deal of promise with regards to true engineering practice, capstone engineering classes. This work in progress paper is about a school district's initial attempt to implement an engineering capstone class in their 8th grade, and our plan to support them in making the class better in the future.

Capstone Pilot
A medium size school district in our area is attempting to implement an engineering capstone course in the 8th grade at their middle schools. They want to provide their students with an authentic engineering design experience where the students plan, design and create a solution to a problem over a semester. These classes focus on the design process, teamwork skills, communication, critical thinking and creativity [2]. These skills are needed in industry. In 1991 the Labor Secretary's Commission on Necessary Skills (SCANS) surveyed industry to identify the most important workforce skills [3]. The commission identified several skills including creativity, teamwork, budgeting skills, communication, leadership, project management, and several others. In education these are sometimes referred to as industry "soft skills." They have been consolidated into the 4 Cs. The 4 Cs in education are collaboration, communication, critical thinking and creativity skills [4]. Most preK-12 education is focused on content knowledge because it can be listed in standards and tested easily. Skill development is not as easy to objectively test. As a result, there are no tests for the 4 Cs and they do not reside in academic standards, and therefore, they are often not emphasized in classrooms. Nevertheless, they are still considered critical skills by industries. They continue to popup on lists of what students should be able to do to be successful in their careers including recent research by Project Lead the Way [5] and the Organization for Economic Co-operation and Development (OECD) [6].

The school district shared their experience with us. The class is within their Career and Technology Education pathway. Ultimately, they want all 8th graders in the district to take this class. During their pilot program, the teachers followed a design curriculum based on an environmental engineering project. The students were supposed to learn about an environmental issue. Then they were to break into teams that would develop a solution to the problem, design and complete some experiments to test a solution, and finally write-up and present a meaningful solution at the end of the semester. The teachers were all trained in project-based learning through the Buck Institute [7]. The assumption was that the capstone course was a typical project-based learning course that lasted a semester.

Unfortunately, the pilot classes devolved quickly. The teachers complained that the groups were either too big or too small. Some students complained of too much work and some complained that there was not enough work. They also noticed that the students did not do much work early in the project. The apparent student perception was that there was still a lot of time until the end of the semester, and therefore there was no need to do much work in advance. Ultimately, the projects were completed, but they were not the quality that the teachers or administrators expected. They did not seem to learn a great deal, and the class did not accomplish its goals.

Similar Project Based Classes in the Engineering School

The 8th grade capstone course they are attempting to create is very similar to classes in the Engineering School, specifically the "Freshman Experiences" and "Senior Design Classes." Many Engineering schools throughout the country have classes like these. They came about from criticism that engineering students were too academic. Professional engineers design and build prototypes. They use their hands to create new technology. In contrast, colleges and universities have a long history of prestigious theoretical academics. As engineering moved into colleges and universities after WWII, naturally it became more theoretical and academic and less hands-on. Even today engineering programs focus heavily on advanced science and mathematics theories. However, by the 1970s industry started to complain that graduating engineers couldn't "do anything" [8]. They did not have the teamwork, creative or communication skills that they needed to design new technology. During the 1980s and '90s, new hands-on design-based courses began to appear. These became the "Freshman Experiences" and "Senior Design Courses." These classes focused on the design process, creativity, teamwork and communications skills [6].

Because of our experiences with these design classes, we believe we may be able to help the district develop a better engineering capstone class for their 8th graders. We developed a proposal for a statewide grant to see if we can apply what we have learned from teaching the Freshman Experience and Senior Design Classes to 8th grade students in capstone engineering classes. The proposal is for a two-week summer camp. The camp will meet for 6 hours each day for 10 days. The time in the class is similar to the amount of time students spend in any given class during a semester, i.e., the time students would spend in a semester long capstone engineering class. We were awarded the grant and will be implementing it this June with the district's students.

Research Question

Our primary research question for this project is, are there common affective teaching practices for engineering design classes at the university and 8th grade?

Of course, there is a great deal that is different between the engineering experiences at the university and a capstone course in 8th grade. University students are much more mature and knowledgeable in math and science, they choose to be in the class, and the classes only meet for an hour, three days a week, to mention a few differences. Nevertheless, many aspects of the class may be suitable for middle school students.

Design Classes

During engineering design classes, students can experience an authentic engineering project. Engineers typically work on teams (Collaboration), require communication skills to explain what they are doing to the rest of the team (Communication), need to think critically about a solution (Critical Thinking), creatively brainstorm their ideas with their team, prototype a solution, and ultimately deliver a product (Creativity). These are the 4Cs that the district would also like to teach through the 8th grade capstone course.

This is a learning environment that is very different from a traditional classroom. Typically, during the first few weeks of the class the students learn what they need to know to build something. They are then put in teams, given a challenge and at the end of the semester they compete in a design competition of some sort. Perhaps the most famous of these classes is the MIT 2.007 class [9]. This class has been the inspiration of several robotics competitions including the FIRST Robotics Competition and BEST Robotics Competition. Dr. Woody Flowers from MIT hosted a TV show based on the class for a while. The class features a six-week build period after which the students compete in a robotics competition. This is a different, and to many, a fun way to apply science and math concepts and to learn the engineering design process.

Teamwork

Teamwork is critically important in an engineering project. Very little can be designed by an individual engineer. Cell phones, cars, and computers require hundreds of engineers working in many different fields constantly collaborating with each other. Engineers must be able to work effectively on a team. They are assigned tasks by the team and need to complete the tasks or the rest of the team will suffer. Our design projects require teams. The teams need to be right sized, and they need to be prepared for common obstacles.

A big difference between project-based learning (PBL) units and design classes at the university is that PBL units expect all the students to learn the same thing. The PBL unit is designed to teach the students content standards [10]. In our design classes we do not expect each student to get the same content out of the class. We expect them to work on interdisciplinary teams. Each team has experts who are responsible for a different system of the project. In our classes they build a robot. The robot has an electrical system, a software system, a mechanical system, a power system, and a drive system. The students focus on one of these systems. As a team they will cover all the systems. By the end of the semester they will have learned much more about their system than the other systems. This works well for us, because it allows our students to explore more deeply the engineering field that might interest them the most while still being exposed to the other systems. Each system represents a field of engineering, electrical engineering, mechanical engineering, software engineering, etc. , Figure 1 Design Project, illustrates the structure of a design project in our courses. Each team member has a task that contributes to the whole project. Each student learns their sphere of information and contributes to the design of that system. This allows us to right size the teams as well. There are only as many members on a team as there are systems. If a member does not have a significant job, they tend to leave the team [8].

Teams also must understand the dynamics of teamwork. There are four common stages that all groups tend to work through: Forming, Storming, Norming, and Performing [11]. Performing is the stage every team wants to reach. However, they need to go through the other stages to get there. A common mistake is all of them taking their part and working on it independently. Near the end of the project they come back to the project and attempt to put the parts together. This is a common solution that never works. Without regular communications with the team, the individual pieces do not fit together.

Project Management

A semester is a long time. A PBL unit usually only lasts two or possibly three weeks [10]. Much of a PBL unit is organized by the teacher. The teams are expected to organize a long-term design project. Therefore, the teams need instruction on project management strategies and tools. Project management is critical if they are going to make the most of their time. Engineers and other project managers use tools like Gantt Charts to manage their time [12]. Gantt charts include a list of the tasks and due dates for the tasks that need to be completed before the project is finished. It also will indicate a critical path. The critical path represents the tasks that must be completed before other tasks can be started. If the tasks on the critical path are not complete, the entire project will be delayed. Sometimes the team needs everyone on the team to be working together to complete a critical task to make sure the task is completed on time. In an Agile team environment this is called a sprint [13].

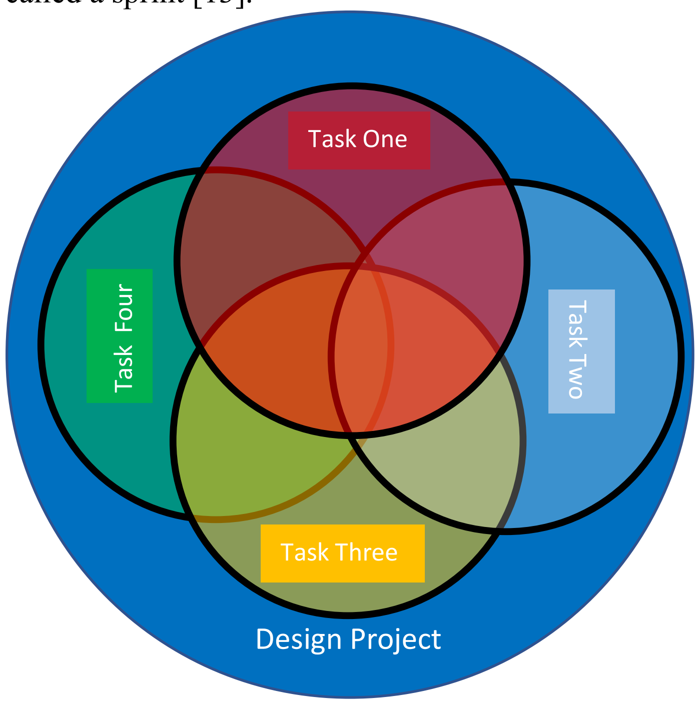

Figure 1 Design Project

Design Reviews

Another important element of the design process is a design review by outside experts. On big projects there can be a lot of design reviews. In a semester we only have a preliminary design review and a final design review. A design review is carried out by outside experts. The experts have technical knowledge of the project and project experience on other similar projects [14]. These experts review the initial plans for the project, ask questions to clarify the design, and provide advice to the project team going forward. After the design review the team normally modifies their design according to the advice from the reviewers. During some projects, the initial design review will be used to eliminate some design projects so that the resources can be focused on the most promising designs. The final design review is at the design competition. It is more of an affirmation of the hard work the design teams have gone through from their esteemed colleagues. It is also a check to make sure the design teams have implemented the suggestions the reviewers made during the initial design review.

Competition
The final competition is the final assessment of our design project. The final assessment could also be a performance, but in any case, it should be a public display of their final design product. A competition is a powerful assessment. In most classes, several students can earn an A. In a competition there will only be one team that will be the best. The stakes are higher at a competition than they are in a typical classroom. Some prefer the assessment be a performance rather than a competition. This also offers public comparison of projects, which often inspires an effort that exceeds other classes. Either a public competition or performance can lead to better learning outcomes.

It is apparent from this discussion that an engineering design class teaches many valuable skills beyond academics. We believe that traditional classes do not touch on these skills effectively. An engineering design class teaches the 4 Cs. We do not believe that the 4 Cs are beyond the comprehension or ability of 8^{th} graders. We believe they can learn how to work successfully on teams; many of them are successful members of sports, dance, or other teams. We believe they are capable of being creative. Research on elementary students has shown that they are very capable of creative thought [15]. We believe they can learn to communicate better and think critically as well. We also believe that they can work on a project over an extended period like a semester, if they are taught some simple time management tools like Gantt charts. If we are successful in integrating these skills into our summer project, we believe schools will be more willing to offer capstone engineering courses at their middle schools and perhaps other grades so that more students can learn industry, and engineering design skills before they graduate.

References

1. NGSS Lead States, *Next generation science standards: for states, by states.* Washington, DC: National Academies Press, 2013. www.nextgenscience.org/next-generation-science-standards.
2. R. Razzouk, & V. Shute, "What is design thinking and why is it important?" *Review of Educational Research*, 82(3), 2012.
3. U.S. Department of Labor, *The Secretary's Commission on Achieving Necessary Skills* (June 1991) [online] https://wdr.doleta.gov/SCANS/whatwork/whatwork.pdf
4. S.Budhai, L. Taddei, *Fostering the 4Cs with technology: how can I leverage technology to teach 21^{st} Century skills*, ASCD Press, 2015
5. Burning Glass Technologies, *The Power of Transportable Skills*, Project Lead The Way Research Report, 2017.
6. OECD, *Getting skills right: skills for jobs indicators,* 2017 [online] http://www.oecd.org/employment/skills-and-work/
7. Buck Institute PBL Works, [online] https://www.pblworks.org/
8. V. C. McGowan1 & P. Bell, "Engineering Education as the Development of Critical Sociotechnical Literacy,"*Science & Education* (2020) 29:981–1005
9. C. Peterson, A brief history of 2.007, the MIT class that inspired FIRST Robotics, January 12, 2016 [online] https://mitadmissions.org/blogs/entry/a-brief-history-of-2-007-the-course-that-inspired-first-robotics/
10. J. Krajcik, C. M. Czernaiak, *Teaching Science in Elementary and Middle School: A Project-Base Learning Approach* Kindle Edition

11. Mary F. Maples Group development: Extending tuckman's theory, The Journal for Specialists in Group Work, 13:1, 1988, pp. 17-23,
12. R. Stevens, K. O'Connor, L. Garrison, A. Jocuns, D. M. Amos, "Becoming an Engineer: Toward a Three Dimensional View of Engineering Learning," *Journal of Engineering Education,* July 2008.
13. M. Hynes, C. Mathis, S. Purzer, A. Rynearson & E. Siverling, "Systematic review of research in P-12 engineering education from 2000–2015." *International Journal of Engineering Education*, 33(1), 2017, pp. 453–462
14. Fabien, B., Vereen, K. "Implementing a Freshman Engineering Design Experience at the University of Washington," *Proceedings of the 3rd International Conference on Higher Education Advances.* Editorial Universitat Politècnica de València. 2017, 1343-1352. doi:10.4995/HEAD17.2017.5603
15. Cunningham, C. M., *Engineering in Elementary STEM Education*, Teachers College Press: New York, 2018