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Infusing Engineering Design into High School STEM Courses

Morgan Hynes, Merredith Portsmore, Emily Dare, Elissa Milto, Chris Rogers, and David Hammer, *Tufts University;* Adam Carberry, *Arizona State University*

Society is recognizing the need to improve STEM education and introduce engineering design concepts before college. In the recent National Academy of Engineers report, *Engineering in K-12 Education: Understanding the Status and Improving the Prospects*, the authors suggest that the STEM disciplines not be treated as "silos" and that engineering might serve as a motivating context to integrate the four STEM disciplines (Katehi, Pearson, & Feder, 2009). Recent research has suggested that integrated technology and engineering design curriculum can serve as a positive model for mathematics and science learning and retention (Ortiz, 2010; Wendell, 2011).

The Tufts University Center for Engineering Education and Outreach (CEEO) strives to improve STEM education through engineering and believes every student should have the chance to engineer. Situated in Massachusetts, the first state to adopt engineering education at all levels in public schools (Massachusetts DOE, 2001), the CEEO supports the belief that engineering education starts in kindergarten and continues to develop throughout their K-12 schooling. We also believe that at the core of K-12 engineering is the Engineering Design Process (EDP). The purpose of introducing students to the EDP is not to have them "build things", a common misconception. The EDP is meant to teach students that engineering is about organizing thoughts to improve decision making for the purpose of developing high quality solutions and/or products to problems. The knowledge and skills associated with the EDP are independent of the engineering discipline (e.g., mechanical, electrical, civil, etc.) and engineering science (e.g., thermodynamics, statics, or mechanics) knowledge that a particular engineering challenge may call upon. Design tasks therefore entail developing the kinds of critical thinking skills commonly associated with engineering and technology literacy. Three key concepts in successful implementation of the EDP are: students are engineers; teachers need to listen to their students; and classroom environments need to change to properly enable learning through the EDP.

Recently, we worked with the Massachusetts State Department of Education to produce a revised engineering design document that describes a learning progression for the EDP from kindergarten through high school. This white paper describes the high school portion of that document geared toward the activities or skills we associate with the EDP as defined by the current Massachusetts curriculum frameworks. This depiction of the EDP implies a cyclical, stepwise process that is rarely the case in solving real-world engineering problems. Oftentimes the task requires some jumping around from step to step, as shown in the figure below.

By adopting this slightly adjusted paradigm, students will recognize that the EDP does not rely upon rigid thinking, but provokes creative and outside-the-box thinking. The purpose of learning engineering design is to encourage students to interact with engineering in hands-on activities as a practical application of math and science knowledge. Through actual practice of engineering, high school students learn that it is not simply building things. Instead, it is a process through which structures are designed, through which clear identification and definition

of the need or problem, research, planning and brainstorming, testing and evaluation, and communication are necessary.

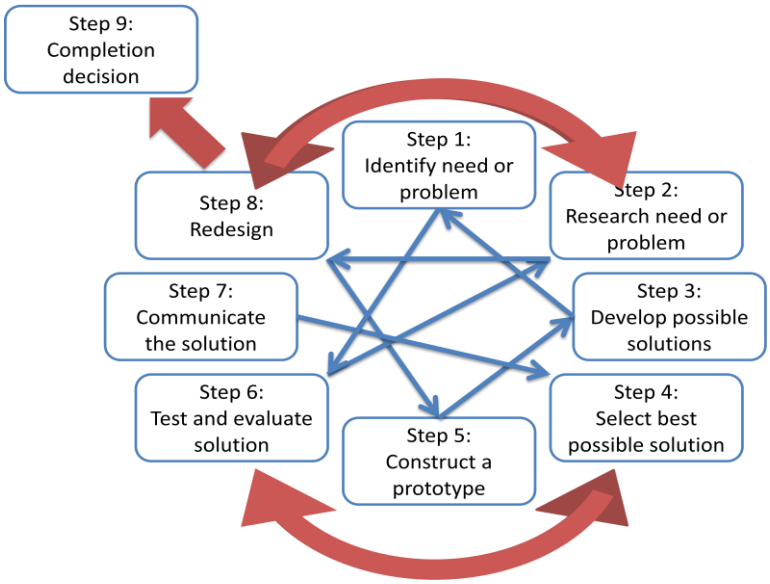

Figure 1 Engineering Design Process

Programs that succeed in improving student learning through design or project-based learning include the University of Colorado at Boulder's First Year Engineering Project, Purdue's Engineering Projects in Community Service (EPICS), Armstrong Atlantic State University's Talented Researcher in Engineering (TRIE) (Goeser et al., 2009), and the US For Inspiration and Recognition of Science and Technology (FIRST), to name a few. While these programs are not specifically created for high school curriculum, they provide positive evidence of students learning through design. Engineering design challenges across the country, such as those sponsored by NASA, are also aimed at interesting students in engineering.

All of the programs listed above, though they differ in their approach in instigating students' involvement in engineering, center around engineering learning through hands-on activities. This approach has been advocated by many, altering the way students learn engineering (e.g. Committee on Engineering Education in K-12, 2009; Crismond, unpublished manuscript; Koehler, Faraclas, Sanchez, Latif, & Kazerounian, 2005). The EDP that we describe below is an integration of all of these concepts and does not necessarily need to be reserved for engineering-specific classes. In fact, courses that focus on design-based experiences, as reported by the Committee on Engineering Education in K-12 (2009) have reported, have shown to "improve student learning and achievement in mathematics and science, as well as enhance interest in STEM subjects" (Crismond, unpublished manuscript).

Provided that students are exposed to the EDP prior to high school, as is now standard in the state of Massachusetts, the proposed CEEO learning progression addresses key aspects of how high school students should approach and solve engineering problems. Once mastered, this progression will enable students to tackle ill-defined problems and lead them to direct their own research on a problem that ends with a successful solution. This progression from beginning designer to informed designer endorses an engineering education progression throughout K-12

(Crismond, unpublished manuscript). While the process challenges students in a different way from their typical school subjects, it has been shown that students eagerly welcome the challenge (Goeser et al., 2009). Instead of sitting in a classroom scribbling down equations and memorizing facts that will be forgotten as soon as the bell rings, engineering design provides students with a vehicle to use all of the science and math material they have been taught throughout their education. By incorporating engineering into the traditional math and science frameworks, the paradigm would shift from "rigid, content driven, discipline-specific course work to a more problem-based engineering decision making model." (Koehler et al., 2005, p. 1)

We were able to construct the following description of the skills and abilities associated with engineering design for high school students using research in the area of K-12 design education where possible, combined with our experience working in K-College engineering education. The following should not be read as a rigid set of guidelines that must be followed, but rather as a set of guiding principles to consider in curriculum design and instruction in high school engineering.

Identify and define problems: High school students are capable of identifying a need or problem in a given situation and should be provided the opportunity to do so. The goal should be for students to deal with ill-defined problems, identify the necessary constraints imposed on the problem, and acknowledge the clients' desired specifications. Classroom challenges should emulate real-world engineering challenges as much as possible. When a teacher asks students to find a problem to solve, s/he is providing students with the opportunity to decompose a given situation in order to frame a problem in their own words (Koehler et al., 2005, Lemons et al., 2010). It is important that the problem is open-ended with many possible solutions (i.e. no one "right answer"). We believe that this approach not only provides students an opportunity to practice important critical thinking skills, but it also increases the likelihood of the students to take ownership of the project because it was not simply given to them by their teacher.

Research the need or problem: Once a problem has been identified, instead of rushing to solve the problem with the first solution that comes to mind, students must conduct some background research. Students should understand that there are many things to consider when solving an issue and recognize that they need to fully explore the challenge in order to be well-informed as to how to solve it (Crismond, unpublished manuscript). As such, engineering challenges and associated curriculum must make the need for and benefit of research clear to the students. It should not appear as something to rush through to satisfy the teacher's request. This student-driven research allows students to comprehend that research is integral to the process of engineering (Ennis & Greszly, 1991), and that it will improve the quality and efficiency of their work. Note that it is highly likely that as students research the need or problem and discover new constraints or ideas that they will be redefining and clarifying the problem.

Develop possible solution(s): Recording multiple ideas for the task takes into consideration the need for planning and teamwork. Students should actively brainstorm in groups to help foster individual learning and creativity (Crismond, unpublished manuscript). Through this process, students work on their communication skills with others and grasp the understanding of tradeoffs (Crismond, unpublished manuscript) while forming their ideas within the problem criteria and constraints (Mullins, Atman, & Shuman, 1999; Radcliffe & Lee, 1989). By using words,

drawings, and prototypes, students can explore and develop ideas with clearly defined specifications (Crismond, unpublished manuscript; Gassert et al., 2005; Gentilli et al., 1999).

Select the Best Possible Solution(s): The ultimate purpose of design is eventually to create an end product that solves the problem at hand. At the elementary level, this usually implies one finished product selected by the teacher. At the high school level, students need to be able to justify and reason their own solution to pursue. This requires that a best possible solution be selected for the individual or group project. What may seem the best for one person may not always seem to be best for another person. This supports the notion that a perfect solution is rarely available to practicing engineers. This step necessitates that students will be able to back-up their ideas with proper consideration of evidence and issues that were discovered through problem definition and research (Dym et al., 2005). This also assures that students use their knowledge of math and science to make informed decisions, constantly assessing each one along the way.

Construct a prototype: Building is often the only concept students have about engineering prior to any engineering design exposure. This is clearly not the case, as the previous four activities describe the need for sufficient planning before construction can begin. The prototype is a representation or model (physical, virtual, or mathematical) of the final solution (Maki & Thompson, 2006). Iterative prototyping until an acceptable product is reached is a key component of this stage (Koehler et al., 2005), allowing students to physically construct a model of the solution (Carberry, Lemons, Swan, Jarvin, & Rogers, 2009). It is important to allow students to fail and learn from those failures as they iterate on their solution. It is not always important that the prototype perform like the intended final solution. Instead, it should demonstrate some functionality or look of the proposed final solution. Note that there may be a number of models developed throughout the challenge that build upon each other or represent different characteristics of the final solution (e.g., size, function, appearance, and feel).

Test and Evaluate the Solution(s): Students must create fair tests based on the constraints and requirements of the problem to judge whether or not their prototype is successful. Elementary students require a fair amount of guidance from their teacher on how to test and evaluate their solution, but high school students are capable of developing their own experimental tests to evaluate their solutions (Trevisan et al., 1998). Determining appropriate testing procedures may cause students to reengage in the research step (2) as they determine what methods and tools will help determine how well their prototypes meet the requirements (Gentilli et al., 1999). At this juncture, students have the ability to recognize that a finished *prototype* does not necessarily mean a finished *product*.

Communicate the Solution(s): Part of engineering is sharing your ideas and findings with others for feedback and marketing purposes. By the time students reach high school they are fully capable of documenting their solution through written documents, presentations, and constructions. The ability to organize information for understanding and clarity is necessary to present ideas to others (i.e. teammates, teachers, and clients): high school students are well aware of how to accomplish this (Gentilli et al., 1999). These presentations should include specifications, performances, issues, limitations, and constraints (Gassert & Milkowski, 2005). By giving an oral presentation, students will communicate their solutions in a language and style

that is understandable by a target audience, which could be their classroom, the entire school, or actual practicing engineers (Dym, et al., 2005). These presentations require that students accurately and completely document information pertaining to their solution.

Redesign: While elementary counterparts at this stage attempt to answer the question of why their design failed or succeeded, high school students focus their attention on redesigning the key problems with the intent to optimize their design (Koehler et al., 2005). Students at this level are able to troubleshoot their problems (Crismond, unpublished manuscript). Each decision they make aims to improve the prototype until a final product has been produced that meets all of the requirements and criteria, as well as passing all of the tests and evaluations.

Completion (leaves the cycle): The very last step of the EDP results in the determination that a final product has been achieved. This product is not simply the result of passing a set of predefined tests, but is based on whether or not students believe they have sufficiently optimized their product to the selected constraints. In this step, students make a decision that they have sufficiently met the design requirements and are ready to implement their prototype as a final product (Gentilli et al., 1999).

Though the description above seems to imply a set path or stepwise approach to the EDP, it is important to remember that throughout this process, students are constantly evaluating and testing their ideas, repeating steps as necessary and sometimes even restarting from the beginning. Occasionally the original idea will have some initial overlooked flaw or a different approach may become apparent through work on the challenge. By integrating this process into already standard STEM courses, students will gain an improved attitude toward and understanding of engineering. Through the act of presenting their work to such groups as teachers, peers, and family members, students can obtain an appreciative attitude towards engineering. We believe that it is critical that engineering design challenges and curricula be intentional in the development of students' process skills and mindful of this in the design of the activities for students.

References

Carberry, A., Lemons, G., Swan, C., Jarvin, L., & Rogers, C. (2009). Investigating engineering design through model-building. Paper presented at the Research in Engineering Education Symposium, Queensland, Australia.

Crismond, D. P. (unpublished manuscript). Contrasting the work of beginning and informed engineering designers in a research-based design strategies rubric.

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D. & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education, 94*(1), 104-120.

Ennis, C. W., & Gyeszly, S. W. (1991). Protocol analysis of the engineering systems design approach. *Research in Engineering Design, 3*(1), 15-22.

Gassert, J. D. & Milkowski, L. (2005). Using rubrics to evaluate engineering design and to assess program outcomes, ASEE Conference & Exposition.

Gentili, K. L., McCauley, J. F., Christianson, R. K., Davis, D. C., Trevisan, M. S., Calkins, D. E., & Cook, M. D. (1999). Assessing students design capabilities in an introductory design class. Frontiers in Education Conference.

Goeser, P., Coates, C., Johnson, W., & McCarthy, C. (2009). Pushing the limit: Exposure of high school seniors to engineering research, design, and communication, ASEE Conference & Exposition.

Koehler, C., Faraclas, E., Sanchez, S., Latif, S. K. & Kazerounian, K. (2005). Engineering frameworks for high school setting: Guidelines for technical literacy for high school students, ASEE Conference & Exposition.

Lemons, G., Carberry, A., Swan, C., Rogers, C. & Jarvin, L. (2010). The importance of problem interpretation for engineering students. ASEE Conference & Exposition.

Massachusetts DOE. (2001). *Massachusetts Science and Technology/Engineering Curriculum Framework*. Massachusetts.

Mullins, C. A., Atman, C. J., & Shuman, L. J. (1999). Freshman engineers' performance when solving design problems. *IEEE Transactions on Education*, *42*(4), 281-287.

NASA. NASA Engineering Design Challenge. Lunar Plant Growth Chamber. Retrieved from http://www.nasa.gov/audience/foreducators/plantgrowth/reference/Eng_Design_5_12.html.

Katehi, L., Pearson, G., & Feder, M. (2009). *Engineering in K-12 education: Understanding the status and improving the prospects.* Washington, DC: National Academies Press.

Ohio Department of Education, Project Lead the Way. Get set! Go! Robotics! Retrieved from www.getsetsite.org/robotics/challenges.htm

Purdue EPICS. EPICS design process. Retrieved from https://sharepoint.ecn.purdue.edu/epics/teams/Public%20Documents/EPICS_Design_Process.pdf on 1/6/10.

Radcliffe, D. F., & Lee, T. Y. (1989). Design methods used by undergraduate engineering students. *Design Studies*, *10*(4), 199-209.

Trevisan, M. S., Davis, D. C., Crain, R. W., Clakins, D. E., & Gentili, K. L. (1998). Developing and assessing statewide competencies for engineering design. *Journal of Engineering Education*, *87*(2), 185-193.

University of Colorado, Boulder. Teach engineering: Resources for K-12. Retrieved from www.teachengineering.org/view_lesson.php?url=http://www.teachengineering.org/collection/cub_/lessons/cub_rockets/cub_rockets_lesson05.xml on 1/6/10.

USFIRST. Welcome to FIRST. Retrieved from https://www.usfirst.org