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## **The engineering design process as a problem solving and learning tool in K-12 classrooms**

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# **The Engineering Design Process as a Problem Solving and Learning Tool in K-12 Classrooms**

## **Abstract**

It can be difficult for teachers to develop engineering curriculum for the classroom due to time constraints, limited access to resources, and lack of knowledge about the benefits and potential success in the classroom. Another challenge to incorporate engineering into the classroom is the teacher's and student's misconceptions about engineering. The engineering design process (EDP) is a decision-making process, often iterative, in which basic science, math, and engineering concepts are applied to develop optimal solutions to meet an established objective. Among the fundamental elements of the design process are the development of objectives and criteria, synthesis, analysis, construction, testing, and evaluation. Teachers can easily incorporate the EDP into existing classroom projects or activities and it can also provide a framework for developing new curriculum modules. The EDP is a great tool that teachers can use in their coursework to enhance their problem solving skills as well as introduce them to engineering disciplines. The EDP was implemented in 7th and 8th grade math and science classrooms over a two-year period through the University of California, Berkeley ADEPT (Applied Design Engineering Project Teams) program supported by the NSF GK-12 program. The EDP was also used in the curriculum of the University of California, Berkeley Pre-Engineering Partnerships summer program for middle and high school students over the course of three summers. The work presented here provides an overview of the module developed for the 7th and 8th grade classrooms. The general use of the EDP was introduced to the students early in the course through short classroom activities and was later explored in more depth as it applied to long term projects. The EDP is also applicable to problems outside of engineering and in the student's everyday lives; this was one of the reasons that teachers were so excited about bringing it into the classroom. The success of using the EDP in the classroom was documented through interviews and surveys of the teachers and students as well as pre and post assessments of the students.

## **Introduction**

The ADEPT (Applied Design Engineering Project Teams) program at the University of California, Berkeley was established to design and deploy a standards-based engineering curriculum for middle schools and high schools (grades 6-12). This program was funded by a National Science Foundation Graduate STEM fellows in K-12 education grant and was designed to integrate mathematics and science concepts applied in engineering projects to inspire secondary students and strengthen the classroom experience of current and future faculty in math, science, and engineering.

One of the resulting curricula from the ADEPT program was focused on introducing students to the engineering design process. ADEPT curriculum development teams combined the best of inquiry and activity-based teaching and learning with cutting edge university research and resources. Each team was made up of local school teachers (Teacher Fellows), graduate students (Graduate Engineering Fellows), university faculty, and advanced undergraduates. Each team member contributed unique perspectives and skills in the creation of discrete curriculum modules. These modules act as exemplary “hands-on – minds-on” engineering projects as model lessons that enrich the learning experience of the entire range of secondary students.

The overall goals of the program were to: engage middle and high school students in doing mathematics and science through engineering projects that strengthen their understanding of core concepts in math and science; inspire and enrich learning for the diverse population of middle and high school students found in urban classrooms; create and sustain a vibrant learning community of teachers, graduate students, undergraduate students and university faculty who work together to develop exemplary curriculum modules; foster a college-going culture among middle school students, parents, and teachers that provides a supportive and attractive alternative to counter--academic pressures confronting students when they make the transition from middle school to high school.

ADEPT teams designed and developed modules to serve the needs of the full range of students in grades 6 to 9, including those who do not learn core math and science concepts with current curriculum and teaching methods. These “hands-on – minds-on” engineering design projects tap into a greater range of learning modalities than current textbook and classroom practices. Second, ADEPT modules serve the needs of students who have mastered the core math and science concepts and are challenged by the open-ended opportunities to integrate these math and science concepts, and apply their understanding in engineering projects that have implications for their lives and their community. Each ADEPT Project Team consisted of one Math and one Science Teacher Fellow, two Graduate Engineering Fellows, a university faculty, and undergraduate tutors. Together they helped secondary students succeed in math and science through comprehensive in-class academic support and engineering project modules.

## **Background**

The engineering design process (EDP) is a decision-making process, typically iterative, in which the basic science, math, and engineering concepts are applied to develop optimal solutions to meet an established objective. Among the fundamental elements of the design process are the development of objectives and criteria, synthesis, analysis, construction, testing, and evaluation. Several experts in the field of technological education have provided strong evidence that engineering design should be the central focus of technological education<sup>1,2,3</sup>. Wicklein proposed that the field of technology education adopt a design-based interpretation on the engineering definition and suggested that the most appropriate approach for infusing engineering in

technology education is by establishing engineering design as the focus. Some key aspects that were the basis for the assertion were that engineering design provides a defined framework to design and organize curricula; engineering design provides an ideal platform for integrating mathematics, science and technology; and engineering provides a focused career pathway for students<sup>3</sup>. While most of the work mentioned here focused on high-school level technology education, the engineering design process should also be considered as a pathway to introduce engineering to all levels of K-12 students. Van Meeteren suggests that the design process is already present in high-quality early childhood programs, particularly those that are constructivist in nature<sup>4</sup>. While this may be the case in a low percentage of schools it has still not been implemented on a large scale. The reason for this could be due to limited amount of time to address state standards, limited resources available to schools, or assessment criteria for engineering education in K-12 curricula. Due to these reasons, the authors used a project that was already part of the teacher's curriculum and adapted it to the EDP.

The design process, the engineering approach to identifying and solving problems, is (1) highly iterative, (2) open-ended, in that a problem may have many possible solutions, (3) a meaningful context for learning scientific, mathematical, and technological concepts, and (4) a stimulus to systems thinking, modeling, and analysis<sup>5</sup>. In all of these ways, engineering design is a potentially useful pedagogical strategy. Analysis is one of the key ideas that is new to K-12 education. Once students select a potential solution, they analyze and evaluate the solution to determine if it is the optimal solution. This step in the process extends beyond just trying to get the "right" answer, but helps students realize that there can be more than one right answer. This type of learning is not typically introduced in early childhood education. The importance of analysis has been addressed previously in literature. Kelley and Wicklein found strong indicators that the engineering analysis phase of the EDP is not typically emphasized in assessment practices<sup>6</sup>. They also point out how literature has proven that one of the major differences between the technological design and engineering design is often the analysis and optimization steps<sup>1,7,8</sup>. The authors of this paper agree with their assessment that without the inclusion of the analytical process to problem solve students often default to a trial and error methodology. The analysis step of the EDP also allows the students to start to make linkages between their prototype, final solutions and the results of testing the prototype or solution.

### **Engineering Design Process and Design Thinking**

One of the true values of engineering study is the development of real-world critical thinking and meta-cognition skills; skills that are adaptive in nature and applicable to areas beyond engineering. However, the development of these skills is commonly left to the humanities. The EDP lends itself to this type of study due to the iterative nature and analysis of varied potential solutions. Also, it is important to point out that the EDP while coined as a design process, can be used beyond design. The curriculum that was developed here used the EDP to address many situations and problems that were not limited to the design of a product or system. The EDP was

chosen as a method to teach the benefits of engineering “design thinking” not purely the subject of design. “Design thinking” is characterized by a set of skills that include tolerating ambiguity, viewing from a systems perspective, dealing with uncertainty, and using estimates, simulations, and experiments to make effective decisions<sup>9,10</sup>. Literature on the design process models suggests that there are two prescriptive models that can be characterized based on the level of abstraction considered and the flow of cognitive focus from problem to product<sup>11</sup>. These distinctions mirror those found in educational literature. Two pedagogical approaches for dealing with open-ended problems and tasks are problem-based learning and project-based learning. The curriculum developed by the authors used the EDP to address both types of learning. For the problem-based learning approach the students used the EDP to find resolution for a real-world problem of their choice. Project-based learning was addressed during the third phase of the curriculum that had the students work in teams to complete a design project, which is outlined later in this paper. Choosing the appropriate model and application of the design process is important for teachers to consider when using it in their curriculum.

Teachers can easily incorporate the EDP into existing classroom projects or activities and can also be used as a framework for developing new curriculum modules. The EDP is a great tool that students can use in their coursework to enhance their problem solving skills as well as introduce them to engineering disciplines.

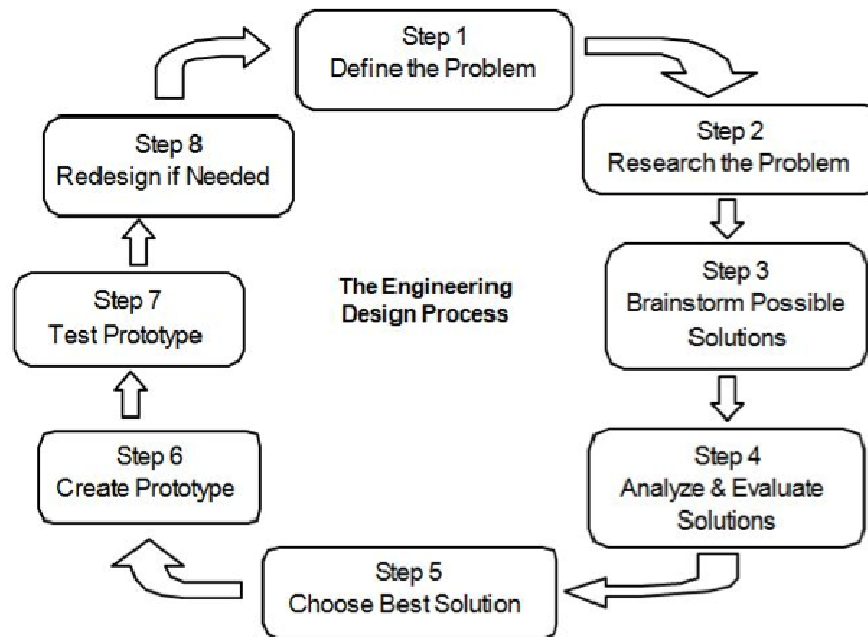
The interests of the instructors were in developing a curriculum that:

- focused on learner-centered, open-ended, and constructivist activities,
- introduced pre-engineering skills that are not typically addressed in K-12 education,
- exposed students to an authentic engineering working environment, included team oriented projects, and
- guided students towards adaptive critical thinking, to engage them in developing meta-cognitive skills.

## **Engineering Design Process Module Overview**

The EDP module used in the classroom was developed using a three-phase approach. The first phase was an introduction to the design process and working through each step as a class. The second phase had each student choose a problem to work through the EDP as a take home assignment. The final phase had the students work together on a design project and complete the steps of the EDP as a group. These phases are described in more detail later in the paper. This module was implemented in two 7th grade math and two 8th grade science classrooms over the course of two years. The general use of the EDP was introduced to the students early in the course through short classroom activities and was later explored in more depth as it applied to long term projects.

During the first phase of the module, each step was defined, explained, and then used in an example problem. The EDP includes eight steps, which are shown in figure 1. While this figure can be used as an initial introduction to the EDP, it does not address the iterative process that the EDP should follow. This should be discussed with the students when applying the EDP to problem solving and design projects. Many different design models have been reviewed<sup>12,13,14</sup>.



*Figure 1: Engineering design process diagram*

The students were given a choice of four potential problems to work through the EDP. The four problems they chose from were:

1. When it rains, my shoes/pants/backpack stay wet all day.
2. I run out of hot water during my morning shower.
3. I can't fit my new furniture through my front door.
4. My hands get tired when I play video games.

The suggested problems were developed from problems or needs from everyday life. For example, one suggestion was if it was raining outside, how to get to school and stay dry. This short design project allowed the students to be exposed to the entire design process before studying specific aspects of the process in more detail. Guiding questions were developed for each step of the process in order to be used as prompts for the students as they worked through the process. The guiding questions for each step are shown in table 1.

<b>Step in the Engineering Design Process</b>	<b>Guiding Questions used as prompts</b>
Step 1: Define the problem	Who? What? When? Where?
Step 2: Research the problem	Where and how would you find more information about the problem?
Step 3: Brainstorm possible solutions	Try thinking of as many solutions as you can, no matter how crazy.
Step 4: Analyze and evaluate solutions	Now that you have a number of ideas, what features are most important in the design you choose? Ex. – Cost, time, weight, etc.
Step 5: Choose best solution	Based on your ideas and analysis, choose the best solution.
Step 6: Create prototype	How would you create a prototype? What materials would you need?
Step 7: Test prototype	How would you test your prototype?
Step 8: Redesign if needed	How will you know if you need to redesign? What are some reasons you might?

*Table 1: Guiding questions for applying the Engineering Design Process*

The second phase had the students use the EDP to work through a pre-selected problem as an individual homework assignment. This was done to reinforce the concepts learned in the classroom activity and to have every student attempt the process on their own. This meta-design asked the students to define a problem. Examples of problems that students came up with included: soccer shoes caused blisters, car for elderly people, and carrying heavy backpacks to school.

The third and final phase of the module had the students work in groups of 3-4 in order to design, build, and test a rocket. The rocket project was already part of the teacher's curriculum and it was adapted by the authors of this paper in order to incorporate the EDP. The EDP was used as the basis for this team project. Before each step of the EDP it was introduced to the classroom as a whole and then the teams could work individually through the process with teacher's assistance if needed.





Figure 2: Visuals to assist in brainstorm activity

Visual cues can assist in student team discussions and engage them in active brainstorming. Several brainstorming techniques such as mind mapping and brainwriting were used. Once students completed the brainstorming session, they were then asked to draft a sketch of three rocket prototypes. These sketches needed to include proper dimensions, materials, and scaling. Engineering drawing concepts were introduced in order to guide the students in the drafting process. The students were also asked to include what materials would be used and to identify the purpose of each component of the design. This was done to encourage the students to use purposeful design techniques and to consider the function of each component. The components could be identified as a form factor or a functional factor, but that had to be decided by the team of students.

Once the drawings were complete, students used a rocket simulation computer program in order to test their three potential rocket designs. The students also incorporated graphing skills to graph the results from their rocket simulation for each of the three rocket designs they tested. Figure 3 shows a portion of the worksheet used to collect the data from the simulation.

Using the following web site determine the height of the rockets with various amounts of water in the body of the rocket. Fill out the data and then graph the results using a line graph. [http://www.ag.ohio-state.edu/~rockets/cgi-bin/design\\_zone.cgi](http://www.ag.ohio-state.edu/~rockets/cgi-bin/design_zone.cgi)

**Rocket A:**

Cone weight:

Body weight:

Tail weight:

Pressure: 50-psi

Maximum height: \_\_\_\_\_

Ounces of water	0	5	10	15	20	25	30	35	40	45	50
Height of flight											

*Figure 3: Screenshot from simulation worksheet*

After the simulation, students chose their final design and modified it accordingly. Before building the final design the students sketched their design and labeled each component with material choice and function of component. A student example can be seen in figure 4. Next, the students constructed their first 3-D prototype of the rocket design in order to go through one round of initial testing before they would have to finalize and build their final rocket design. The testing of the rockets occurred outside using a rocket launcher that the teacher made from an online tutorial. Figure 5 shows images from the rocket launching activity. The students would place the rocket appropriately on the launcher oriented as decided by their team. The students had three trials and the best one was kept on record for final assessment by the teacher. The success of each student teams' project did not just focus on how well their rocket performed but also how well each student followed and implemented the engineering design process steps. Due to the success of the module in the classroom the same engineering design methodology was implemented in the teacher's egg-drop project the following semester.

## Final Rocket Design

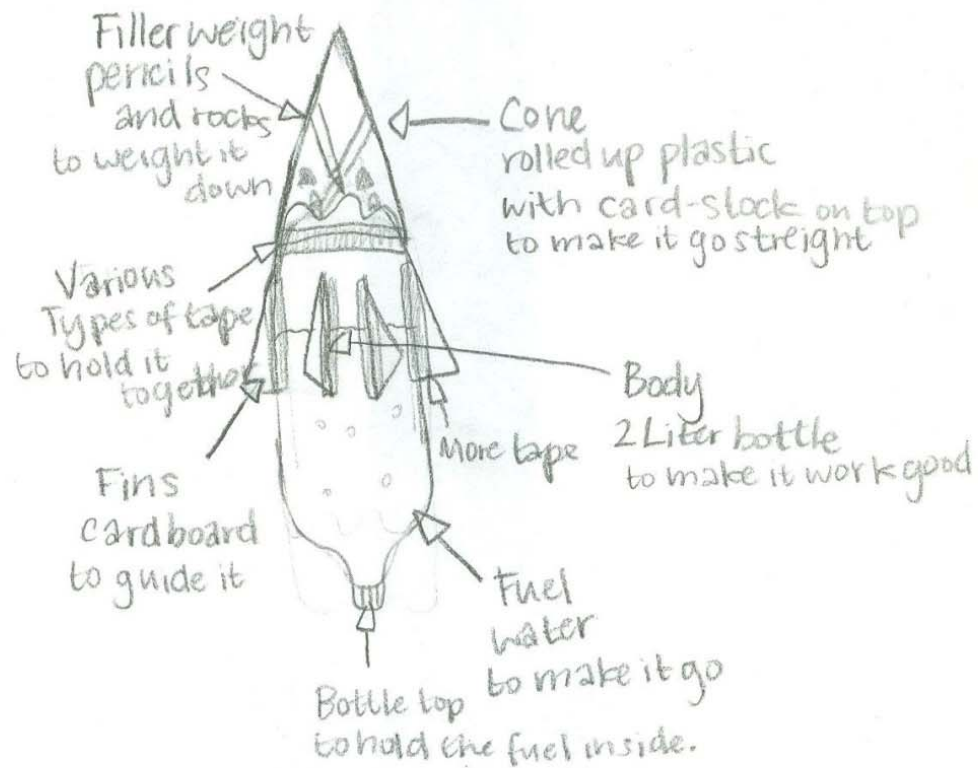
Name: \_\_\_\_\_

In this final design, you will be designing an ideal rocket from your experience and observation of all the launches.

Each part of the rocket must include:

- \_\_\_ Label
- \_\_\_ Materials used including what was used to attach that part.
- \_\_\_ Purpose

### Diagram



Use the check list to make sure you include items in your diagram

Check list:

Rocket Part	Label	Material used	Purpose
Body	X		

Figure 4: Final Rocket Design Worksheet



*Figure 5: Images of rocket launching*

## **Conclusions**

Sustainability was an important aspect of the modules developed over the course of the ADEPT program. College design classes are now incorporating sustainability in the design process as an important aspect the designer should always consider. A design based on green or sustainable design extends beyond baseline engineering quality and safety specifications to consider environmental, economic, and social factors<sup>15</sup>. The authors of this paper believe there should be no exception to this when introducing the engineering design process to K-12 students. Sustainability should be part of the initial conversation to consider the life cycle impact of products or processes that are being developed.

The module developed not only introduced the students to engineering, but also allowed them to apply the principles of engineering to their everyday lives as well as assist in teaching the standards required by the state. One of the biggest benefits the teachers identified was that the framework could be adapted to any project that was already part of their curriculum and provided the students with lifelong problem-solving skills and strategies. The teachers expressed enthusiasm about how easily they could integrate the EDP into their already existing curriculum and adapt their lessons plans to fit the form of the EDP. The teachers as well as students really liked how the EDP divided problems into steps and manageable sections of work. This modular approach allowed the entire project and design process to not be so overwhelming for the students.

To gauge the success of using the EDP in the classroom, interviews were conducted with the teachers and students, surveys were given to the teachers and students, and pre and post assessments were given to the students on the subject area that the module focused on. Throughout the module and project activities, there was a lot of excitement and positive feedback from both the teachers and the students. Student engagement was noted by the facilitators throughout the course of the module.

Feedback from the students consisted of an increased understanding of what engineering was based on pre and post survey results, an increased excitement about the material presented in class (as observed by the authors and the teachers), and an increased understanding of the material presented in the classroom based on pre and post assessment scores. Students also commented that having the clear steps of the EDP made it much easier to follow along and to understand the assignment. Several students also mentioned that they felt relieved that they would have multiple opportunities to work on their rocket design and testing. Previously they had not had the chance to make design changes and therefore relied on an initial build and test method for their rockets.

In an attempt to measure the correlation between the teacher's belief that implementing the EDP into their curriculum could be helpful to student learning and the student's actual learning, pre and post assessments were given to the students to determine the effectiveness of student learning as well as student interest before and after the project. The results overwhelmingly confirm that student learning and student interest increased and over 90% of the students were impacted positively by the program. After talking with students and teachers and reviewing the results of the pre and post assessments, it was determined that this experience and using the EDP helped students do better in the subjects taken in middle school by giving them a structured framework and approach to solve problems; it gave them a guideline to follow and it allowed them to break the problems down into smaller pieces to work on and allowed them to follow a flow chart method to help decide what step to take next. In addition, linking their curriculum to engineering and working on hands-on projects engaged the students on a deeper level and interested them in the subjects they were studying. Future work should address the quantitative assessment of the qualitative results presented here and test the success of these modules in additional K-12 classrooms and across multiple grade levels.

After the successful implementation of this project, it was incorporated in other classrooms and grades within several local schools. The success of this could not be possible without the close collaboration between the authors of this paper and the participating teachers. In conclusion, the approach and methods presented in this paper can be employed and leveraged successfully by other teachers and the content and subject matter could be altered in order to be engaging and age appropriate for the students.

Sample modules from the program can be viewed at:

<http://coe.berkeley.edu/cues/pep/adept/index.html>

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