Teaching and Learning Open-Ended Problem Solving Throughout a New Degree Program

Prof. Jenifer Blacklock, Colorado School of Mines

Dr. Jenifer Blacklock is the Assistant Department Head in the Mechanical Engineering department at Colorado School of Mines. Jenifer is active in the Undergraduate Curriculum in the Mechanical Engineering department and is an advocate of using hands-on-learning tools to help develop strong math, science and engineering foundations.

Prof. Jered H Dean, Colorado School of Mines

Jered is Director of the Mines College of Engineering and Computational Sciences Capstone Design Program and is passionate about teaching students engineering through project based learning. He received both his BS and MS degrees in Engineering from Colorado School of Mines. In addition to leading capstone, Jered is the faculty adviser for the Mines SAE Baja team, Anonymous Right Brains Club, and CSM Racing Club.

©American Society for Engineering Education, 2015
Teaching and Learning Open-Ended Problem Solving Throughout a New Degree Program

Overview

The concept of ‘Design’ is a significant challenge for faculty to teach and students to learn. Last year through a survey, we asked students what ‘design’ and ‘engineering design process’ meant to them. We were surprised to see that the majority of our students did not identify open-endedness as a key feature of these statements. In response to this survey, integrated with the development of a new degree program, a standard and simple definition of the key elements included in a good engineering design process was created. This standard definition and implementation of open-ended design problems throughout the curriculum, together with student learning assessment tools, have been used to improve students’ ability and comfort in addressing open-ended design problems.

The Mechanical Engineering (ME) department at the Colorado School of Mines (Mines) has a unique opportunity to revisit fundamental concepts taught throughout the undergraduate curriculum. In Fall 2013, the department went through the accreditation process for a B.S. in Mechanical Engineering degree, which was a transition from the previously offered B.S. in General Engineering with a Mechanical Specialty. In July 2014, the ME department became ABET accredited under the new degree offerings. The split of the former Engineering Division provided an opportunity for the faculty to take a new look at the curriculum and begin to implement significant changes throughout the curriculum, starting with ‘design’ and enhancing students’ abilities to solve open-ended design problems. Having approximately 250 ME students graduating every year, this proved to be a difficult feat in itself.

One of the key changes to the ME degree program included implementation of open-ended design problems or challenges throughout the degree program. Open-ended design problems are challenging for students when they are confronted with the fact that there is no ‘right numerical answer’ for them to achieve. The uncertainty of no one ‘right’ answer is unnerving to students. Open-ended design problem-solving is a difficult concept for faculty to teach to students and for students to learn and internalize from faculty because addressing open-ended design problems requires an integrative approach that is not taught in analytic courses. In this study we have developed and refined the curriculum to produce students who are capable of, and confident in, holistically addressing open-ended problems in a design context.

We have started the process of tracking our students’ comfort in addressing open-ended problems. To achieve this, we have taken a “baseline snapshot” of the current ME classes in order to have a clear understanding of the current state of our students’ abilities. We have conducted preliminary surveying that strongly indicates our students are largely incapable of tackling Open-Ended Problems and that our
students do not understand Design. We will implement surveys throughout our undergraduate curriculum to track students’ performance and improvement over time. We will follow students throughout a five year period and analyze their ability to solve Open-Ended Problems while making changes to the curriculum, one step at a time.

**Background**

In the last two years, the Mechanical Engineering (ME) department at Colorado School of Mines (Mines) has had a unique opportunity to revisit fundamental concepts taught throughout the undergraduate curriculum. In Fall 2013, the department went through the accreditation process for a B.S. in Mechanical Engineering degree, which was a transition from the previously offered B.S. in General Engineering with a Mechanical Specialty. In July 2014, the ME department became ABET accredited under the new degree offerings. The split of the former Engineering Division provided an opportunity for the faculty to take a fresh look at the curriculum and begin to implement significant changes throughout the curriculum, starting with ‘design’ and enhancing students’ abilities to solve open-ended design problems. Having approximately 250 ME students graduating every year, this proved to be a difficult feat in itself.

One of the key desired changes to the ME program included implementation of open-ended design problems or challenges throughout the degree program. As stated by Simon et al, Design is widely considered to be the central activity of engineering.\(^1\) The desire to implement these open-ended design challenges was aided by the creation of a new sophomore level design course. However, the integration with existing, core technical courses proved more challenging than anticipated. Many papers have discussed several barriers to the advancement of effective engineering design focusing on classroom-based practices.\(^2\)\(^-\)\(^4\)

Open-ended design problems are challenging for students when they are confronted with the fact that there is no ‘right numerical answer’ for them to achieve. The uncertainty of no one ‘right’ answer is unnerving to students. Open-ended design problem-solving is a difficult concept for faculty to teach to students and for students to learn and internalize from faculty because addressing open-ended design problems requires an integrative approach that is not taught in analytic courses. In this study we have developed and refined the curriculum to produce students who are capable of, and confident in, holistically addressing open-ended problems in a design context.

There are several models for teaching design, many which consist of project based learning models.\(^5\) Several papers have mentioned that faculty feel that the leaders of engineering departments and schools are unable or unwilling to recognize the intellectual complexities and resources demanded to support good design education.\(^6\) With that said, we have found it important to develop a simplified model
that can be easily understood, translating the basic, fundamental principles of engineering design to all faculty members.

**Student Surveys**

We aspire for our students to be holistic, system thinkers who are capable of tackling difficult Open-Ended Problems and Design challenges. However, as the faculty began to discuss curricular changes, it was clear that we needed metrics to track progress towards that end. To achieve this, we have taken a “baseline snapshot” of the current ME classes in order to have a clear understanding of the current state of our students’ abilities.

In the spring of 2014 a survey was developed to explore current student strengths and weaknesses in open-ended problem solving and design. A survey was developed to track students progress through a newly developed curriculum with an emphasis on Open-Ended Problems and Design challenges.

The following five questions were asked of students based on a 1-7 likert scale:

All questions on a scale of 1-7(1 being Agree Strongly, 7 being Disagree Strongly):

1) I have confidence in approaching and solving open-ended design problems where there is no correct answer.

2) I am comfortable performing research on open-ended design problems and I am able to use this research to start solving an open-ended design problem.

3) I have the ability to design a new piece of equipment, process or product.

4) I am capable of manufacturing a working prototype of a new piece of equipment, process or product.

5) I have confidence in performing an analysis and evaluating the validity of its results.

Initially the survey was given to over 200 students in 3 courses with 58 responses. The preliminary surveying strongly indicates our students are largely incapable of tackling Open-Ended Problems and that our students do not understand Design. With that stated, we will continue to implement surveys throughout our undergraduate curriculum in order to track students’ performance and improvements over time. We will follow students throughout a four-year period and analyze their abilities to solve Open-Ended Problems while making changes to the curriculum, one step at a time.
Throughout the degree program, students are given surveys at the end of each year to fill out along with a final exit survey. We have used these surveys as a tool to track students understanding and comfort level of solving open-ended design problems using the standardized design process approach that was created. This will allow us to track students throughout their degree program and also receive final data upon their graduation. Additionally, courses mapped in Table 1, provide students a similar survey at the end of each of the courses to track students progress in specific courses as well.

Analysis of Assessment and Student Surveys

Initial, baseline results show that students who are starting out in the new degree program have confusion about what design really is. Additionally, it was found that there is a lack of common language between the students. Most students who responded to the questionnaire stated that they felt comfortable with design and open-ended design problems, however when asked to define both Design and an Engineering Design Process, student where not able to give accurate answers. With that stated, it was clear that a commonality of language be disseminated throughout the curriculum in order for students to recognize both an Engineering Design Process as well as what Design actually entails.

Standardization of design throughout the curriculum

The survey results highlighted that for design across the curriculum to succeed, a common language is essential. At Mines ten faculty members, who teach design at various levels throughout the engineering curriculum, sat together to discuss how design was taught in their respective classes and what common language could be agreed upon. Together, the faculty members developed a framework for engineering design that both the students and faculty could reference (Figure 1).
Figure 1: A standardization of an approach to the Engineering Design Process

Four key areas of excellence were identified by the faculty as crucial to successful student design: clear problem definition, thoughtful exploration of possible solutions to the problem, appropriate application of engineering analysis, and quality implementation of the final solution. In addition, designers must engage with the project stakeholders, manage the project, and document their work. All of these things must be addressed in an iterative nature as the design progresses.

All four areas listed in Figure 1 need to be appropriately addressed for a design project to succeed. However, each design challenge will require a custom design process, utilizing a mix of tools applied at the appropriate times.

As the faculty discussed the areas of excellence further, a list of degree-level learning objectives emerged for each of the identified areas. The learning objectives are as follows:

1. **Problem Definition**
   a. create a clear, concise goal statement for an engineering challenge;
   b. identify the stakeholders for an engineering challenge and identify their needs;
   c. prioritize stakeholder needs and determine appropriate ways to engage them for a given engineering challenge;
   d. define a set of engineering requirements for an engineering challenge;
   e. articulate the functional and/or spatial basis of an engineering challenge;
f. create a verification plan\textsuperscript{1}, tied to requirements, for an engineering challenge;
g. create a validation plan\textsuperscript{2}, tied to stakeholder needs, for an engineering challenge;

2. Problem Exploration
   a. develop multiple, overall conceptual design solutions to a given engineering challenge;
b. develop ideas using basic ideation techniques such as brainstorming;
c. develop ideas using analytic ideation techniques such as mind mapping or morph matrices;
d. communicate the prior art of an engineering challenge;
e. benchmark competing products relevant to a given engineering challenge;
f. communicate the breadth of the solution space of an engineering challenge.

3. Analysis
   a. utilize back-of-the-envelope calculations to check the feasibility of a design concept;
b. utilize qualitative decision methods to select the most promising solution for a given challenge;
c. utilize decision methods, supported by calculations and/or quantitative data, to select from multiple design options;
d. define the cost of goods sold (COGS) for a proposed design solution;
e. estimate the production cost of a proposed solution;
f. complete a sensitivity analysis;
g. apply appropriate technical knowledge to solve a design challenge;
h. articulate the environmental, societal, and/or economic impacts that engineering interventions can produce in contemporary settings;

4. Implementation
   a. develop an engineering solution for a given challenge, within constraints;
b. communicate an engineering solution via a detailed design documentation package;
c. construct a looks like/feels like prototype;
d. construct an engineering prototype by integrating off-the-shelf components;
e. construct an engineering prototype involving multiple custom-designed and constructed components;
f. construct a prototype of a system composed of multiple subsystems;
g. execute a verification plan for an engineering challenge;
h. execute a validation plan for an engineering challenge;

\textsuperscript{1} For the purpose of this paper, verification involves proving that a design meets the technical requirements and specifications for the project.
\textsuperscript{2} For the purpose of this paper, validation involves proving that a design meets the initial customer needs identified for the project.
5. **Communication**
   a. communicate ideas using hand-sketches;
   b. communicate system boundaries and input/output using a black-box diagram;
   c. communicate an proposed solution using pseudocode;
   d. communicate a proposed solution using graphical means such as a logic diagram or process diagram;
   e. prepare and deliver an oral elevator pitch style presentation;
   f. prepare and deliver an oral technical, design review presentation;

6. **Project Management**
   a. create a project management plan to address an engineering challenge;

**Mapping Courses**

When surveying the Mechanical Engineering (ME) curriculum at Mines it is clear that some courses are targeted at teaching design, while others are focused heavily on engineering analysis. The design courses and several, select lecture courses were chosen from the curriculum and the previously identified design learning objectives were mapped to each course. A key focus of the mapping effort was to promote the idea that both the “Design-centric” and “Non Design-centric” courses can support the enhancement of student design abilities if properly coordinated.

**Design-centric Courses**

Several courses in the curriculum have adapted different types of design challenges for students to solve with the explicit intent of going through the design process steps. These courses include:

**EPICS I:** The centerpiece of the Design EPICS (Engineering Practices Introductory Course) cornerstone course is an open-ended design problem that students must solve as part of a team effort while working with a client. EPICS aims to build students’ confidence in solving open-ended problems and communicating.

**Introduction to Mechanical Engineering:** The Introduction to Mechanical Engineering course is a sophomore level course were students learn programing in conjunction with Arduinos, sensors and breadboards. Students learn the basics behind programming in MatLab and are given toolboxes with about 15 different sensors along with Arduinos and breadboards. After the basics are understood, students are asked to do three projects throughout the semester, each of which gets progressively harder and more complex. The final projects, students are asked to build their own weather station and provide appropriate outputs to the user.
**Field Session**: Field Session is a three-week intensive hands-on engineering course which students complete during the summer after their sophomore year. During Field Session, students are presented with several design challenges and competitions in ME related fields.

**Machine Design**: Machine Design consists of a 4 credit hours course, 3 hours of lecture with a 1 credit hour Design Studio. During this time, students are asked to work on 3-4 (depending on the semester and instructor) open-ended design problems. The solution to these design problems must be figured out by the students. Many of these solutions consist of FEAs of parts, assemblies as well as hand calculations. Students are also asked to find the overall failure points of the system. Generally, the final project in this class asks students to build a final project and test the product as well.

**Senior Design**: Senior Design consists of two semesters, both three credit hours long. During this time, students have a creative multidisciplinary design experience emerging from combined efforts in civil, electrical, mechanical, and environmental specialties in engineering. This course has been designed to comply with the ABET guidelines that require the engineering design component of a curriculum to include at least some of the following features: development of student creativity, use of open-ended problems, development and use of design methodology, formulation of design problem statements and specifications, consideration of alternative solutions, feasibility considerations and detailed system descriptions. Further, it is essential to include a variety of realistic constraints such as: economic factors, safety, reliability, aesthetics, ethics and social impact.

One of the major drivers of mapping the learning objectives for design across the curriculum was the development in the first semester of the Introduction to Mechanical Engineering course. The faculty involved in developing the course began comparing the items being taught in the EPICS I cornerstone course to those expected in the Senior Design capstone course. These end-caps, plus feedback from the department industry advisory panel, and findings from the student survey previously discussed painted a picture of poor coordination.

Table 1 presents the mapping of the engineering design learning objectives to the design-centric courses throughout the curriculum. Since all of these courses were focused on design, the primary objective for this mapping effort was to mindfully support the guided mastery process of the students towards comfort with ever more complex challenges. In addition, the mapping kept the instructors from duplicating content and gave each instructor explicit targets to focus their efforts on.

<table>
<thead>
<tr>
<th>Course</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPICS151</td>
<td>a, b, c</td>
<td>a, b</td>
<td>a, b</td>
<td>a, c</td>
<td>a</td>
<td>-</td>
</tr>
<tr>
<td>Into to</td>
<td>d, e</td>
<td>a, b</td>
<td>a, c, d</td>
<td>a, d, g</td>
<td>b, c</td>
<td>-</td>
</tr>
<tr>
<td>MechEng</td>
<td>Field Session</td>
<td>Machine Design</td>
<td>Senior Design I</td>
<td>Senior Design II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>--------------</td>
<td>----------------</td>
<td>----------------</td>
<td>-----------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>f</td>
<td>a, b</td>
<td>a, b, g</td>
<td>a, b, e</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>a, b</td>
<td>a, b, g</td>
<td>d</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>f</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>c, f, g</td>
<td>a, b, g</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>a, b, c, d,</td>
<td>c, d, e, f</td>
<td>a, b, c</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>e, f, g</td>
<td></td>
<td></td>
<td>d, e</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>e, g, h</td>
<td>a, b, f, g, h</td>
<td>f</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 1**: Mapping the primary engineering design learning objectives in design-centric courses throughout the ME curriculum

Coordination of these courses, and the minor tweaks needed to align the curriculum, were relatively easy to implement due to:

1. The creation of the Introduction to Mechanical Engineering course from scratch as part of the mapping process,
2. The buy-in from the directors of both the capstone and cornerstone programs, and
3. The fact that a small group of faculty within the department are the primary drivers for these sort of open-ended interventions.

**Non Design-centric Courses**

It is more challenging to add open-ended design challenges in the core technical courses across the curriculum. Several key issues make integration challenging including:

1. Pressure to “cover the textbook” in courses like dynamics and thermodynamics,
2. A lack of financial and physical resource allocation to the classes to support hands-on construction projects, and,
3. Resistance of some instructors to deviate from well-established lesson plans.

For these reasons, a different approach must be taken to integrating design. By mapping the design learning objectives across the curriculum, elements of design can be embedded without requiring drastic changes to many of the core technical courses. A simple example of this type of integration is the use of pseudo-code as a precursor to any of the required MatLab assignments in Thermodynamics. Pushing students to solve the given simulation challenge abstractly before dealing with syntax maps closely to discussions in design regarding the importance of understanding and exploring function before form.

With this logic in mind, several courses were selected for integration of a limited set of design learning objectives. These courses include: Dynamics, Thermodynamics, Computer Aided Engineering (CAE), Manufacturing Processes, and Heat Transfer. All of these courses hit on several of the pillars in the engineering design process.
The mapping of learning objectives to the non design-centric courses throughout the ME curriculum is detailed in Table 2.

<table>
<thead>
<tr>
<th>Course</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamics</td>
<td></td>
<td>a</td>
<td></td>
<td></td>
<td>d</td>
<td></td>
</tr>
<tr>
<td>Thermo</td>
<td></td>
<td></td>
<td>b</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAE</td>
<td>a</td>
<td>a,f</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing</td>
<td>a</td>
<td></td>
<td>d,e</td>
<td></td>
<td>d</td>
<td></td>
</tr>
<tr>
<td>Heat Transfer</td>
<td></td>
<td></td>
<td></td>
<td>b</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Mapping engineering design learning objectives to non design-centric courses throughout the ME curriculum

Implementation of the new design learning objectives into the non design-centric courses identified in Table 2 has not yet been completed. Over the coming semesters the learning objectives will be rolled out.

Discussion

It is important for students to continuously be exposed to both (1) key tools and techniques that are useful in addressing open-ended design challenges and (2) a standardized framework for thinking about how the tools fit together. The proposed learning objectives have served to identify key tools and techniques that all students should be exposed to. The design framework is intended to provide a mental model that students can reference.

The learning objectives were mapped in a logical progression from their initial freshman experience through Senior Design. The first course that students see is EPICS I where students learn the basics behind engineering practice and are introduced to the design framework. Following EPICS I, a new course, MEGN200 Introduction to Mechanical Engineering, was introduced into the curriculum. This course is taught around project based learning, where students learn fundamental material at the beginning of each of the three projects and are then required to implement those basic concepts learned to complete open-ended design projects, with each of the design process step pillars being hit on. After MEGN200, students complete ME Field Session, which is a three-week intensive hands-on engineering course. During this time, students are presented with several design challenges and competitions in several ME related fields.

After students go through the Field Session experience, several courses have been selected to present students with design problems either throughout or at the end of the semester. These courses include; Dynamics, Thermodynamics, Computer Aided Engineering (CAE), Manufacturing Processes, and Heat Transfer. All of these courses hit on several of the pillars in the engineering design process. Finally, students in their senior years, take two semesters of Senior Design which brings them back to the full engineering design process pillar system. At this point, students should feel
comfortable starting and solving open-ended design problems and their abilities to do well in Senior Design, as well as the ability to please their clients should see significant changes in the next few years to come.

**Future Work**

From initial surveys and assessments, changes have been made to design-centric and non design-centric courses. We have implemented a mapping of engineering learning objectives in both design-centric and non-design-centric courses to better understand students’ ability to learn specific objectives. This understanding of curricular changes allows us to continue with ongoing evaluations and monitoring the ME curriculum, every semester. Changes to the curriculum will be tracked and will continually be followed. Additionally, it is important that faculty are understanding of these curricular changes to the curriculum. Many papers have stated the importance of getting faculty on-board with engineering design curricular changes, and the challenge of doing so. Integration of a training program for instructors will be instilled into the department starting summer 2015. This training program will assist instructors with both design-centric and non design-centric courses and help them to develop open-ended design challenges for students and assist in what learning objectives should be followed in each of the courses. The program initiation will include all courses mapped thus far. Additional tracking of changes in mapped courses will continue to be assessed.

**Conclusions**

As a faculty, we are keenly aware of the need to improve the well-roundedness of our students so that they are capable of looking at a problem holistically and from a system perspective. We see the engineering design process and Open-Ended Problem Solving as vehicles for developing well-rounded engineers who are ready to enter the workforce. In the Mechanical Engineering department, we would like to see our students graduating with not only the comfort, but also the ability to solve open-ended design problems. Throughout the next 4-5 years we will be tracking students throughout their course work, through an exit survey, and through course assessments to gain further understanding and track students abilities and comfort levels in solving open-ended design problems.

**References**


