AC 2005-118: INCORPORATING OPEN-ENDED PROJECTS INTO A MACHINE ELEMENTS COURSE

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Incorporating Open-Ended Projects into a Machine Elements Course

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1 Introduction

Mechanical engineering students typically take a “Fundamentals of Machine Elements” course in their third year of study. For the last several years, students at the University of Texas at Austin take a redesigned course that combines hands-on projects within a traditional classroom format of homeworks, tests, and lectures. Integrating projects into the curriculum is part of a larger, multi-faceted departmental effort called PROCEED (PROject CEntered EDucation)\(^1\), which actively promotes projects across the mechanical engineering undergraduate curriculum. PROCEED encourages instruction that integrates course projects in order to advance active, socially constructed learning that draws upon a student’s knowledge of theory and principles. That is, students in PROCEED-based courses are going beyond note taking, homework and testing by doing hands-on activities and thinking about what they are doing.

Students entering this machine elements course often lack hands-on experience with tools and machines. Furthermore, in combining this with their few experiences in solving open-ended problems, it appears that students are not ready to apply their theoretical understanding to real problems. This course focuses on teaching the fundamentals of mechanical components: both their functional behaviors and the purpose for their various geometries. One common problem with this course within the modern mechanical engineering curriculum is that it essentially encapsulates the bulk of mechanical engineering knowledge that existed prior to the Second World War. While much of the course material is not conceptually difficult, there is an immense amount of definitions and simple relations for various components. Simply teaching these component fundamentals does not properly outfit students with the mechanical intuition that engineers a hundred years ago achieved under an extensive mentorship program. Furthermore, the need to redesign this course has been apparent within the department’s goal to bridge the gap between lower-level analysis courses with senior level design courses.

In this paper, we present our project-based approach to teaching machine elements as well as expand upon our past presentations of this material\(^2, 3\). The project-based learning in this course improves students’ abilities in making connections across various engineering topics and in mastering less tangible skills such as “mechanical intuition.”
2 Course Description

One prevalent challenge in teaching machine elements within the modern mechanical engineering curriculum is that it essentially encapsulates a large amount of mechanical engineering knowledge – most of which is compiled empirically through laboratory tests over the span of a hundred years or more. In order to combat the tendency to fall into the tedium of presenting numerous mechanical elements and their behaviors without providing students a context in which they deepen their understandings, we have rewritten the course objectives as follows:

- To demonstrate improved mechanical intuition,
- To effectively work in teams and apply interpersonal skills in an engineering context,
- To practice selecting and/or designing components,
- To better communicate mechanical concepts, and
- To describe how engineers design to avoid failure.

These outcomes were developed to better address the abilities of the current students and to better prepare them for senior year design activities and the current variety of careers in mechanical engineering. In order to meet these goals, students complete a series of class projects which complement the traditional lecture-homework-test format. The projects are performed by groups of students (3 or 4 members per group) and incorporate aspects of laboratory dissection and design project construction. The projects are structured as extended homework assignments that preserve classroom time for discussing the content of selected machine element topics. Over the fourteen weeks of a full semester, the three projects occur in tandem with course topics. In all three projects, students define their own focus by finding engineering artifacts to study. Typical products are those which the student already owns or can acquire with a modest investment (under $30). By having students participate in choosing what they study, we foster their enthusiasm and encourage their exploration of how a device works and its likely modes of failure.

In the first project, students prepare for and participate in a “show-and-tell” on the second class day. While, the project’s goal is to test the abilities of students in communicating mechanical concepts, the cursory and perhaps more important aspect is to have students overcome their intimidation for tinkering with such artifacts and become enthusiastic about how such products are designed. The second project begins in the third week of the course, midway through the first five week treatment of mechanical component failure modes. In the project, students apply course material to the analysis of a single component. Ultimately, the goal is to “reverse engineer” the component and predict the factor of safety used by the engineers. The project requires that students estimate applied loads and reduce an often complex geometry to something that is analyzable. The resulting reports contain a detailed description of the component, how it was analyzed, and other potential ways it could be designed. In the final project, students expand their analysis of a complete artifact that includes multiple machine elements. Project activities for project 3 are similar to those of project 2, but now the team of students must determine within the complete artifact which components are most susceptible to failure and the best candidates for redesign.
3 Course Implementation

The course outline used in this project-centered machine elements course is illustrated in Table 1. The class format still includes lectures, reading assignments, and four semi-cumulative exams in addition to the three projects presented here. Since these projects add a level of complexity to the course, deadlines for homeworks, exams and projects must be managed carefully.

3.1 Project 1: Show-and-Tell

The “Show & Tell” activity is presented to the students on the first day of the class. The assignment reads:

Report on one of your favorite machines or mechanisms. Write up a half page description (approx. 350 words). If possible, bring the device to class on next Tuesday for discussion or include a picture in your report. Cite what you think are interesting or clever parts of the design including shapes, linkages, etc. Comment on the forces acting on one or more of the components and predict where stresses might be the highest within the components.

This activity mainly focuses on the students’ abilities to describe mechanical behavior and design. It is important to note that many mechanical engineering students today lack the experience in ‘tinkering’ – a quality believed to be ubiquitous in the budding engineer. Many students are motivated to engineering simply because they have shown proficiency for math and science and are enticed by the potential for a secure and well-paying career.

The project also offers an opportunity for the instructor to gauge and be reminded to what degree students have learned machine elements terminology over the years. Often, students within this project are unwilling to disassemble their chosen artifact and thus chose areas where the design will fail on the surface of the product as opposed to elements inside.

These assignments are to be graded carefully since the feedback given at this stage should ideally bolster students to actively learn how everyday artifacts function and how they are designed to
function. If feedback is too harsh students will be demoralized since they had such difficulty with a seemingly simple task. Students at the junior level have proved their muster in handling challenging and math-intensive freshman and sophomore classes like calculus, thermodynamics, kinematics, and fluid mechanics. However, it is easy to see how little they have gleaned about the practicalities and complexities of most engineering design problems.

3.2 Project 2: Single Component Analysis

The second project begins in the fourth and fifth weeks of the class where students are finishing a study on the strength of materials and the ways in which components are designed to avoid failure. Following the approach of many machine elements textbooks, the class begins by focusing on various ways in which components fail (i.e. yielding, fracture, fatigue, etc.) followed by detailed discussions of typical machine components like gears, bearings and springs. This project is focused on the material learned thus far by charging them to study of a single component that they can readily observe as opposed to a device composed of numerous elements. The project description is stated as:

In this project, your design team will be responsible for analyzing an existing engineering artifact. Imagine you are working for a consulting company that has been hired to determine how safe a particular design is. Your study will determine the safety factors in the design and suggest what the minimum values for the design parameters (dimensions, material choice) could be to reduce the cost.

The assignment further lays out four tasks are their respective deadlines.

- **Step 1: (due in week 1 of assignment)**
  The first thing you must do is choose your group for this project. Your group will consist of no more than three people and you may work only with your assigned partners and the course instructors. You may not use any materials produced by another student, except your assigned partners.
  Please inform the TA or instructor of your group as soon as possible.

- **Step 2: (due in week 2 of assignment)**
  Find an engineering artifact (consumer product, or fixture) that is subject to constant and fluctuating loads. Some examples are: the awning at your apartment, the pedal crank on your bike, or the chair you’re sitting in. Brainstorm ideas with your teammates. Your idea needs to be approved by the TA or the instructor.

- **Step 3: (due at end of assignment)**
  Analyze it completely for failure.
  - What are the loads? How do they fluctuate? What are the locations of concern (pick at least 2)?
  - What are the stresses at these locations? What does Mohr’s Circle look like for these locations? What about the $\sigma_1-\sigma_2$ plot?
  - Create a spreadsheet in Excel or program in MATLAB to organize your calculations. All values in the spreadsheet or program must be clearly labeled/commented. Display intermediate results, as well as the final output.
  - What is the Safety Factor at these locations? Is it being overloaded?
  - How small could the artifact be if a Safety Factor of 1 was used?

- **Step 4: (due at end of assignment)**
  Develop conclusions and recommendations about the artifact? Was it designed well? How could the design be improved? What simplifications did you make in your analysis that might have accounted for possible erroneous answers?

Similar to the first project, students are given a great deal of freedom in how to go about completing this project. They work in teams to complete the report and must seek out additional resources to help them approximate loads and material properties.
The final reports are typically only a thousand words but are interspersed with pictures, equations, and spreadsheets. The difficulties in grading the Project 2 assignments generally arise from the quality of the written passages. Often homework assignments assigned from textbook are easier to grade as the grader is fully aware of the details of the problem and the proper procedure. However, in this open-ended project approach we, as graders, must rely on the statements provided by the students. Text written to justify approximate values is particularly welcome and enlightening. They show that students are able to actively seek out properties of their artifact or find similar or supporting materials that lead them to such approximations.

3.3 Project 3: Product Emulation using LEGO®

In the last five weeks of a fourteen week semester, students undertake the “LEGO® Reverse Engineering Project.” This project charges students with the task of recreating an existing mechanical artifact with the LEGO Mindstorms™ kits. Since this project is performed along side lecture material pertaining to a series of specific machine components, the focus is on identifying such components within an existing artifact.

First, we present the students with the scenario that they are working together to create a competing product to their chosen artifact as is shown at the top of Figure 1. They are charged with the task of scrutinizing their competitor’s design by “reverse engineering” it to determine how it functions, how it might fail, and how it might be better designed to avoid failure.

After getting their artifact approved in the first week, they must present what they have discovered about the chosen product in the preliminary analysis. This is usually due within the third week of the project. In this preliminary analysis, the students address the internal behaviors of the device and predict possible modes of failure. From this point, they begin the reconstruction of the artifact to create their LEGO model in the construction phase of the project. On the last day of the class, each group presents their results to the class and submits a twenty page report comparing and contrasting their model to the actual artifact.

While LEGO is not an ideal medium for these advanced students, the activity of emulating a product allows them to note intricacies in the design of the original project that was not evident in the initial dissection. Furthermore, many students have devised clever solutions to overcome the discrete nature of the LEGO components. In a way, the LEGOs achieve the mechanical engineering analogy to the electrical breadboard in that they provide a quick way to construct a variety of electromechanical systems. In fact, the use of LEGOs in engineering education has been shown to be useful in a number of American Society of Engineering Education publications⁸, ⁹, ¹⁰.

While many students perform the preliminary analysis or dissection questioning how and why the artifact was designed the way it was, they often end up praising the engineers’ ingenuity after the construction phase. Furthermore while becoming proficient LEGO designers does not necessarily make the students better engineers, there is a vibrant dialogue that takes place between students working on different projects. Essentially in helping one another construct their LEGO prototypes, the students exchange strategies for designing with the LEGO (as is similar to the LEGO Design Clichés presented in Martin)⁸, and discuss issues with mimicking behaviors in actual devices. This interaction further benefits the learning objectives presented above. Through
In this project, your design team will be responsible for “reverse-engineering” an existing product. Imagine you are working for a company that wants to produce a competing product, and you are trying to discover how the competing products were designed.

Deliverables:
11/08/01 Product Approval
11/20/01 Preliminary Analysis
12/6/01 LEGO device and Final Report
@ final exam Return Kits

1 Product Approval
Within a week you should meet with your team and decide on what product you will be modeling. Choose a relatively simple consumer product or toy (a cordless screwdriver, NERF gun, etc.) that everyone in your group is interested in. The product must have moving components of some sort and preferably a power train. As a group, find your instructor during office hours or after class and get your idea approved.

2 Preliminary Analysis
Once your product has been approved, get it (if you don’t already have it) and take it apart to see how it works. Identify at least two locations or situations where failure would be an issue. Draw the free-body diagrams for these two cases and predict/estimate the applied loads. From these loads calculate the stresses and determine a factor of safety. This report should be no more than 12 pages.

3 LEGO device and Final Report
For the Project 2 Exposition on the last day of class, you will be required to bring in a working prototype of your “reverse-engineered” product along with the device that was modeled. This prototype should emulate the motion (not necessarily the forces) of the original product using basically LEGO components (you may construct additional components if you wish out of cardboard, etc.). The model does not need to be to scale. Each team will have a controller-brick, which can be programmed using the LEGO software. Your prototype can be augmented to include a closed-loop control (where a quantity that is sensed is used to control the motor driving the motion). If the prototype is so simple that it does not require the controller brick, then your team should try to improve the design to automate the product in some way.

4 Final Report
Write a report no more than 20 pages that includes:
1) A description of your product
2) The rationale behind developing the unique features and the conflicting goals of the design. For example, what were the challenging decisions that the designers faced? Is the design based on minimizing cost, maximizing safety, etc.?
3) The failure analysis of original product (as in the above Preliminary Analysis).
4) The comparison of motions between the product and your LEGO prototype. How and why do they differ? Do power constraints of the LEGO prevent modeling velocities exactly? If so, does the LEGO model scale well to the actual product (This is a good place to apply vector-loop equations)?
5) Drawings or pictures of your model and the actual product.
6) A Discussion section which addresses issues such as:
   a. How well did the LEGO prototype correspond to the actual product, and why. Include ideas of what improvements could be made given more resources (more parts, either LEGO or otherwise).
   b. Possible improvements that can be made based on the failure analysis.
   c. Possible improvements to the design, which can include alternate product configurations.

5 Return Kits
On the final exam date, your 3 member team must turn in the entire sorted LEGO kit (with your prototypes disassembled). You will get a 0 on this project if the kit is not turned in at this time.

Figure 1: Handout for the LEGO Reverse Engineering Project
this project, students feel that they gain a better sense of mechanical intuition as well as an understanding of how and why components are designed in a certain manner. This is supported by the survey results shown later in Section 5.

4 Examples

The following figures (Figures 2 and 3) shows several of the LEGO models and their actual artifacts that have been created in the last nine semesters that this project has been issued. These projects shown here were chosen merely on the clarity of the pictures and to illustrate the variety of products that are modeled in this class. Often, the artifact being modeled is on a different scale.

Figure 2: Three additional examples from Project 3: a) a hand mixer, b) a circular saw, and c) a toy front-end loader.
than the LEGOs, and hence scale models are sometimes created. In the past, the best projects do not necessarily have models that closely match the appearance of the artifact, as the many groups focus mainly on capturing the range of functions that the product performs. In the written reports, the better projects address what factors of safety must have been used in the design of various components within the artifacts.

Figure 3: Four examples from Project 3: a) a hand drill, b) a fishing reel, c) a record player, d) a handheld back massager.
5 Description of Study and General Methodology

While the project has been well received by both students and faculty, we wanted to look at discrete course components to see what aspects influence student learning and whether or not these components supported the learning objectives for this course (as shown in Section 2). In summary, the projects were intended to support new course objectives that re-emphasize machine elements as a course to bridge engineering analysis and engineering design courses.

Since the traditional approach to covering numerous elements and their failure characteristics is maintained in homeworks, tests, and lecture, we are interested in knowing if the projects are more effective approaches to the new course objectives. To assess the benefits of the project, a short survey was given to the students after finishing both Project 2 and Project 3 in both the fall and spring semesters of 2004. Of the 96 students who took the class, 85 of them filled out the survey after Project 2 and 77 after Project 3. These students have an average age of 21 years; 16% of them are female; and they have an average grade point of 3.3 (out of 4.0).

5.1 Quantitative Survey Results

The survey asked students to rate how successful each of the five course activities was at accomplishing each of the five learning objectives. These activities and objectives are summarized below in Table 2.

<table>
<thead>
<tr>
<th>Course Activities</th>
<th>Learning Objectives</th>
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<tbody>
<tr>
<td>1. Lectures</td>
<td>1. demonstrate improved mechanical intuition</td>
</tr>
<tr>
<td>2. Homework</td>
<td>2. effectively work in teams and apply interpersonal skills in an engineering context</td>
</tr>
<tr>
<td>3. Studying for Exams</td>
<td>3. practice selecting and/or designing components</td>
</tr>
<tr>
<td>4. Project 2</td>
<td>4. better communicate mechanical concepts</td>
</tr>
<tr>
<td>5. Project 3</td>
<td>5. describe how engineers design to avoid failure</td>
</tr>
</tbody>
</table>

A graphical and tabular presentation of the results is provided in Figure 4. In Figure 4a, we show the light solid orange bar as the average of the three non-project course activities: lectures, homeworks, and studying for exams. These are compared to the averages for projects 2 and 3 for each of the learning objectives (the actual numerical value for the averages is shown in Figure 4b). Furthermore, the error-bars indicate the spread of two standard deviations (one positive, one negative) for these averages. It appears that the students rate the projects as being more successful in accomplishing all five learning objectives. Figure 4c shows the results of completing a study of the significance of these averages. In order to claim that the means are truly independent, we must calculate the probability that these means could come from sampling the same distribution (t-test analysis of paired two sampled means). In this study, we conservatively state that “statistical significance” occurs when the probability in less than 0.005. It appears, as shown in Figure 4c, that the students view project 2 and 3 as being significant improvements in the way they achieve all of the learning objectives. The only time significance is not shown, is when project 2 and 3 are compared to each other.
The results of the class survey show that both projects 2 and 3 are more significant activities to the students’ achievement of the learning objectives.
5.2 Qualitative Survey Results

In addition to the scaled responses on the student surveys, we collected comments from the students on the projects. Four open-ended questions were posed on each of the survey forms and several key statements are provided in Table 3. As the statements indicate, the students appear to enjoy the projects and understand the benefits the projects have towards the course objectives. In terms of project improvements, the students often indicate that they would like more time and resources (more LEGO, and measurement equipment) as well as guidance in what assumptions can be made within their project analyses.

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<tr>
<th>Questions on the Projects</th>
<th>Illustrative Comments</th>
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<tbody>
<tr>
<td>Describe Project 2 in terms of appropriateness and effectiveness</td>
<td>“Project 2 is highly appropriate since it integrates all of the concepts we’ve used this far.” “It challenged me to look at a mechanical system in a way I never had before.” “The project was extremely helpful in visualizing all the formulas we have used in the past.” “Project 2 is designed for us to see how the theories in this class apply to a real-world situation and analysis.”</td>
</tr>
<tr>
<td>Describe if and how Project 1 helped with Project 2</td>
<td>“Project 1 got the ball rolling for the thought and reasoning needed for the class as a whole.” “We could conceptually understand how the forces break down and affect the machines.”</td>
</tr>
<tr>
<td>Suggestions for improving Project 1 or 2</td>
<td>“More consultation time with teacher and TAs.” “Have each group set up at least one meeting with the professor to go over the project, add comments, and check on status of group dynamics.”</td>
</tr>
<tr>
<td>Describe Project 3 in terms of appropriateness and effectiveness</td>
<td>“It was fun and gives us hope that engineering is not just about formulas.” “Good opportunity to get hands-on with concepts described in coursework.” “Project 3 was a seamless advance from Project 2.”</td>
</tr>
<tr>
<td>Describe if and how Project 2 helped with Project 3</td>
<td>“It got my mind in the right mode for analysis.” “Yes we did failure modes both times.” ”It provided a good template for the more complex failure analysis in this project.”</td>
</tr>
<tr>
<td>Suggestions for improving Project 3</td>
<td>“Make presentations mandatory and graded.” “More Lagos.” “I wish the LEGO had more different shapes.”</td>
</tr>
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</table>
5.3 ABET Survey Results

In order to prepare for ABET2000, the mechanical engineering department at the University of Texas at Austin has recently implemented an online tool to gather feedback from students about how well a given project achieves the stated mechanical engineering outcomes. This survey was recently administered at the end of the fall 2004 semester and details can be found in Schmidt and Jones\textsuperscript{11}. The survey asks students to self-report the quantity, quality, and improvement (QQI) of their learning on 5-point Likert scale.

Figure 5 shows a comparison of the machine elements class discussed here with the included projects to other machine elements courses that currently do not include such projects. It appears that students see the project course as better at accomplishing the first seven ABET outcomes over the non-project course, however, given the unbalanced comparison in the number of survey.

![Graph comparing project-based and non-project-based classes](image)

**Figure 5**: A comparison of the results of the QQI survey\textsuperscript{11} between the project-based machine elements class presented here, and other non-project based machine elements classes.
responses (only a small number of students in the non-project course elected to respond) it is
difficult to draw definitive conclusions at this time.

6 Conclusions
The need to develop more project intensive courses in engineering is being studied and
implemented throughout the country. Furthermore, design activities within mechanical
engineering are being introduced earlier in many curricula. Since students are not as exposed to
many design activities early on at UT, students come into this class armed with a more
theoretical background. This course thus bridges their existing theoretical background to
practical applications. This connecting approach is accomplished by maintaining the lecture-
homework-test format of an analysis course and introducing group project to complement the
lecture material and expose students to the open-ended nature of engineering.

Of course, many students will enjoy hands-on activities over traditionally taught activities. Since,
it is not enough to simply have a content class of students, we gathered feedback on whether the
course instructional strategies, including these projects, accomplished the stated course
objectives. Given the results illustrated in Figure 4, it appears that all instructional elements of
the course are needed to provide a cohesive learning experience. One might think that exams and
the act of preparing for them might be strictly viewed by students as a required process in higher
education and while it is the lowest measure in this study, they still find that these activities
enhance their learning. The lectures were intended to help build upon the students’ practical
knowledge base and it appears that the students were able to make this connection. Overall it is
clear from the data gathered that the projects are providing the students the experience they need
to feel more confident and ready for senior-level design courses. Based on the student comments,
more resources (e.g. TAs and materials) are needed when students are tinkering in classes. While
efforts are underway to meet these needs, we have to maintain that perfect design circumstances
are not realistic and that our students can benefit from the proactive, investigative perspective
that these projects provide.

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Biographical Information

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Dr. Matthew Campbell received his PhD from Carnegie Mellon University in the summer of 2000. He is currently an Assistant Professor at the UT Austin in the ME Department. His research focuses on theories of engineering design and how the computer can be leveraged to solve complex and conceptual design problems. His teaching activities include undergraduate Machine Elements (as described in this paper), a graduate class in optimization, and a collaborative Engineering/Art Project class.

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Dr. Kathy J. Schmidt is the director of the Faculty Innovation Center for the College of Engineering at The University of Texas at Austin. In this position, she promotes the College of Engineering’s commitment to finding ways to enrich teaching and learning. Dr. Schmidt works in all aspects of education including design and development, faculty training, learner support, and evaluation.