Teaching Machine Design through Product Emulation

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1 Introduction

It is widely accepted that in order to learn complex technical material well, some form of active experimentation or "hands-on" activities are required. Traditionally, in engineering education this occurs through laboratory experiments or through design projects. In laboratory experiments students observe the physical phenomena that is presented as theory in the classroom often through *dissecting* complex artifacts, for example, examining the thermodynamics of a refrigeration cycle by studying a refrigerator. Design projects provide a different experience for students, as it allows them to work together on complex problems where the best solution is not known and is complicated by the influence of countless practical matters. This paper describes a new class project that incorporates both qualities of laboratory *dissection* and design project *construction*. It is referred to as *emulation* and has proven to be both an effective and well-liked approach to teaching the fundamentals of machine component design.

The machine elements course at the University of Texas at Austin is taken by mostly junior-level mechanical engineering students. This course is focused 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. It can be a daunting task for any instructor as the amount of material to be taught is both immense, and yet, sometimes only historically interesting. Fortunately, the instructor is relieved from teaching conceptually difficult material as many of the relationships are derived from empirical experiments as opposed to first principles and differential calculus. As a result however, the class tends to be taught in a very content-intensive manner – full of definitions and simple relations for calculating component behaviors and component failure. Furthermore, these courses in machine component fundamentals are still expected to outfit students with the mechanical intuition that engineers a hundred years achieved under an extensive mentorship program.

In order to combat the tendency to fall into the tedium of presenting numerous mechanical elements and their behaviors, a novel experiment has been developed at UT Austin. 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. In order to accomplish this, students *dissect* an existing product, discover how it functions, analyze it for possible modes of failure, and *construct* an alternative prototype using the LEGO kits. This project has now been undertaken for three long semesters (14 week) and has proven to be effective at improving students' intuition about machine design while escaping the tedium that traditionally plagues this class. In the remainder of this paper, we will discuss the learning philosophy used in this project, followed by a thorough description of the tasks that students perform. Then, we will show some past examples along with an assessment of the effectiveness of the project.

2 Learning Basis

The various instructors of machine elements course at the University of Texas at Austin have, over the years, established a set of objectives that they would like to see students learn from the class. These are:

1. an understanding of how various mechanical behaviors are achieved
2. an understanding of the various types of mechanical components
3. an understanding of how engineers choose and/or design components
4. an understanding of how engineers design to avoid failure
5. the ability to communicate mechanical concepts better
6. and an improved mechanical intuition.

This list includes broad goals that are both difficult to teach as well as to learn in the traditional classroom setting. As a result, we sought to borrow from the Kolb's experiential learning model that is shown in Figure 1 to address these objectives from a variety of standpoints. In brief, Kolb[1] proposes that students must engage in four distinct learning activities to properly gain knowledge in a given area. Often learning initiates at the top of the cycle with concrete experiences (step 1) from which the students is guided to observations and reflections (step 2). From such reflections, one is able to generalize to deduce global phenomena (step 3) which can then be validated through testing (step 4). Often, the content-driven machine elements approach to teaching has focused mainly on the first two steps, which has prevented the students from gaining much in the way of the mechanical intuition.

In addition to completing the steps in Kolb's model, this project also allows students to play the "actor" role as opposed to the traditional "receiver" role in the classroom (this distinction is described in Svinicki and Dixon[2]). While such classroom activities often require more time than the traditional use of lecture time, students gain a great deal of insight by describing their individual projects to the class which directly supports the fifth objective above of

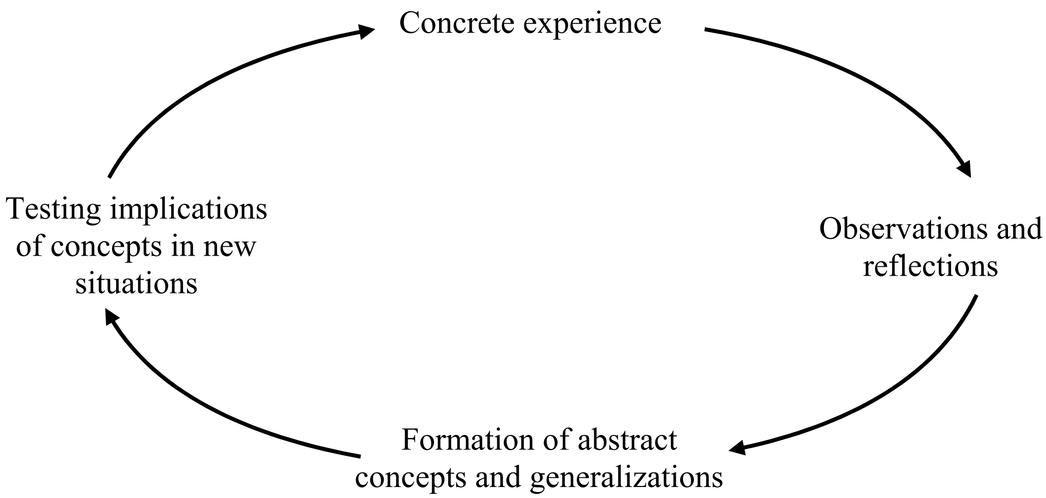


Figure 1 : Kolb's Model of Experiential Learning[1]

communicating mechanical concepts better.

The first stage of the project involves the *dissection* of an existing mechanical artifact that is chosen by the students. A preliminary analysis of the device is required from the students whereby they address the internal behaviors of the device and predict possible modes of failure. The importance of this stage of product *emulation* is that it fosters in students the art of "tinkering". Usually, it is assumed that most engineering students, especially mechanical engineering students, have spent countless hours of their childhood taking apart old toys or helping their older siblings or parents with minor auto repair. Often, the machine elements course can intimidate those students who were not exposed to or discouraged from tinkering as children. These students often benefit from classroom activities such as this that require them to solve mechanical problems that are not presented in textbook form.

The second stage of *emulation* is the recreating of the product using the LEGO Mindstorms kits. This *construction* phase finds the students pushing the limits of the LEGO kits. Many students have devised clever solutions to overcome the discrete nature of the LEGO components. This *construction* process forces students to reexamine how the problem was solved in the actual artifact, which can make them notice subtle details about how the original components were designed or manufactured. 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[3]), and discuss issues with mimicking behaviors in actual devices. This interaction further benefits the learning objectives

Week	Lecture Material	Projects
1	Review of Stress Analysis and Failure Theories	
2		
3	Shafts and Bearings	
4		
5		Proj. #1: Gear Train Project
6	Gear Trains and Fatigue	
7		
8		
9	Bolted Joints and Springs	Proj. #2: Lego Reverse Engineering Project
10		
11	Clutches and Brakes	
12		
13	Mechanisms, (Four-Bar linkages, etc.)	
14		

Figure 2: Calendar for the Junior-Level Machine Elements Course. The Lego Reverse Engineering Project is initiated in the ninth or tenth week of the semester.

presented above. Through 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 in Section 5 (Assessment).

3 *Description of Approach*

The LEGO Reverse Engineering Project is initiated in the ninth or tenth week of the term (see Figure 2). Students are organized into groups of three or four members and each group receives a full LEGO Mindstorms kit. Twenty-five kits (LEGO Product #9790) were purchased for this course along with the accompanying software and some supplementary kits for extra parts for $6000. These kits were chosen because they are useful medium for quickly modeling machines and LEGO products are a familiar and flexible media for capturing a significant range of electromechanical functions. 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. Furthermore, this use of LEGOs in engineering education has been presented in numerous ASEE publications[4, 5, 6].

Figure 3 presents the handout that students receive at the beginning of this project. First, we present the students with the scenario that they are working together to create a competing product to their chosen artifact. 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 (*dissection*). This is usually due within the third week of the project. 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.

Grading for the project is mostly based on the quality of the final written report (65%). Only five percent of the grade is based on the preliminary analysis since the analysis is reworked as part of the final report. The remaining 30% is assigned to the quality of the presentations and the LEGO models. A panel of judges comprised of faculty and teaching assistants is assembled and outfitted with the following questions in order to evaluate the remaining presentation and models.

- How well did the prototype function? Was it robust/repeatable?
- How well did the prototype capture the functions of the product?
- Did the team find ways around the limitations of the Lego parts?
- Did the team identify differences in configurations of product and prototype?
- Did the team identify differences in functionality of product and prototype?
- How well did the team understand why certain functions were impossible/difficult to model?
- Did the team talk about possible improvements that could be made (both to the prototype and the actual product?

Since the students are aware of this criteria and the impression that their results have on the judges, the quality of the presentations and models has been quite exemplary as is shown in the next section.

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.

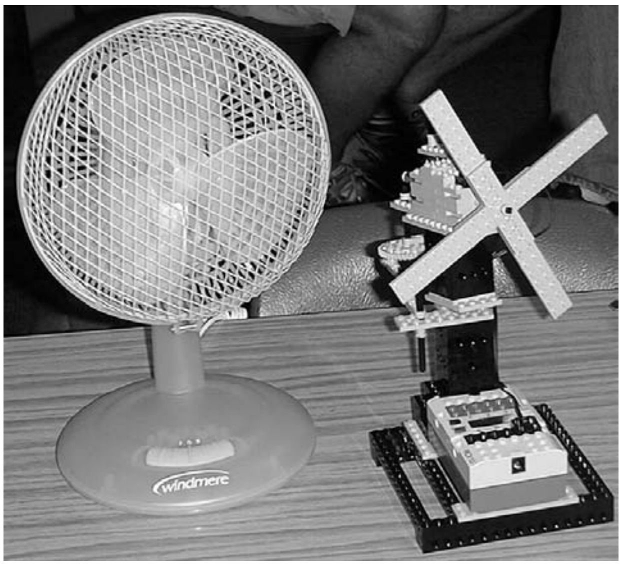
5 Return Kits

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.

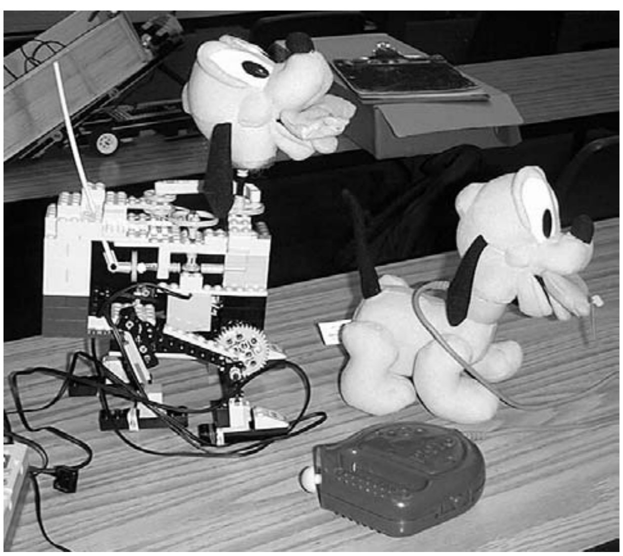
Figure 3: Handout for the Lego Reverse Engineering Project

4 Examples

The following figure shows several of the LEGO models and their actual artifacts that have been created in the last three 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 than the LEGOs,



(a)



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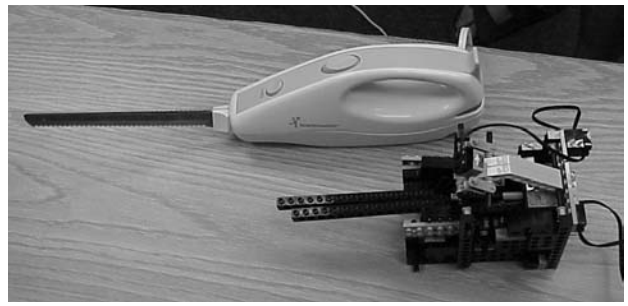

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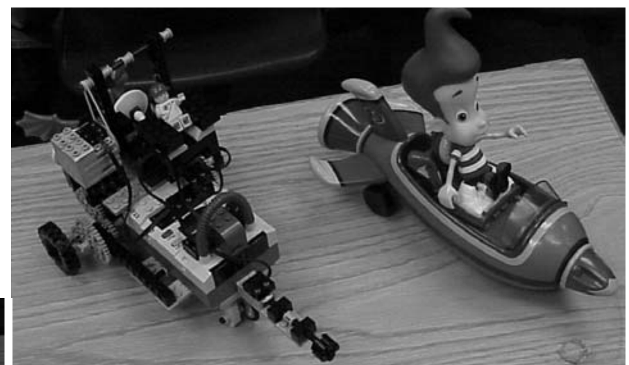

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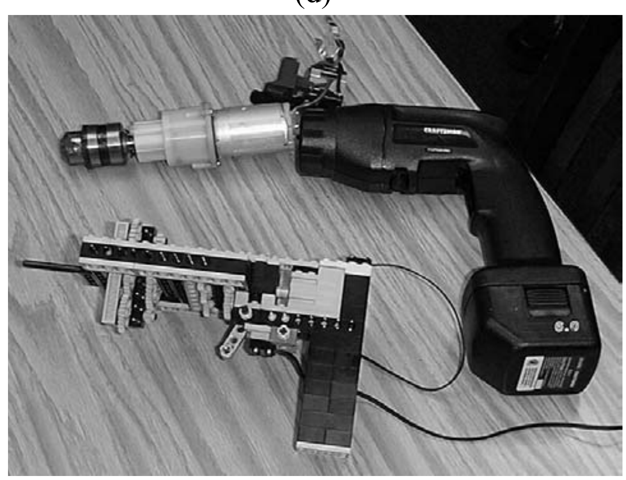

(e)

Figure 4: Five example projects from the LEGO Reverse Engineering Project: (a) a small fan, b) a toy walking dog, c) an electric knife, d) a toy car with ejecting passenger, and e) a hand-held drill.

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 the judges' criteria above and go into depth about what factors of safety must have been used in the design of various components within the artifacts.

5 *Assessment*

While the project has been well received by both students and faculty, it is necessary to test whether or not it supported the learning objectives for this course (as shown in Section 2). To assess the benefits of the project, a short survey was passed out to the students after the class was finished. Of the 39 students who took the class, 36 of them filled out the survey in this past fall semester (Fall 2001). The survey asked the students to rate which instructional component that helped them in learning each of the objectives for the course.

Figure 5 shows the results of the survey. Students were asked to rank the effectiveness of each instructional component in the class for each of the learning objectives (presented in Section 2). In addition to regular lectures, homeworks, and exams, the class had two projects and a "Show & Tell" group activity. The first project (a project to choose gear teeth ratios and calculate stresses

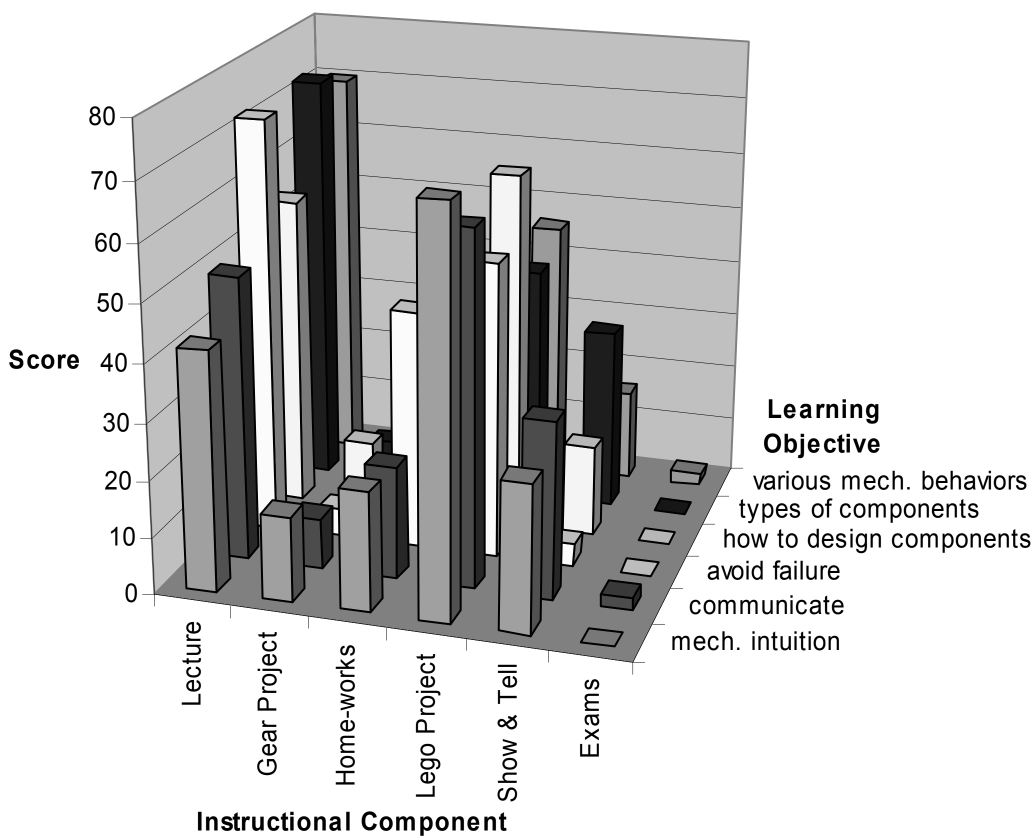

Figure 5: Results from end of the semester survey

in Microsoft Excel) and the Show & Tell activities are not described here (Show & Tell is described in brief in Wood and Wood[6]), but also support the student as "actor" as opposed to just being a "receiver" of course material.

It can be clearly seen in Figure 5, that the majority of students found lectures and the LEGO project as their main vehicle for learning the course objectives. This was confirmed by performing a chi-square statistical analysis on the data. Lectures were voted the statistically most significant instructional component in learning objectives 1, 2, 4 from Section 2. The LEGO project was the statistically most significant instructional component in the remaining three objectives. That is, the LEGO project provided the best way to improve mechanical intuition, learn how to communicate mechanical concepts better, and learn how engineers choose and design components.

With these results, it appears that the LEGO project significantly adds to the students learning of machine components. This survey, however, is based on the opinions of the students and the results may be skewed by what aspect of the class the students found most enjoyable. The course has been gaining the reputation of being the "LEGO course" which is sometimes viewed as being more challenging and time-consuming than its counterpart courses. In order to further assess the benefits of this project, a formal test will be conducted with the students before and after the project in the coming Spring 2002 semester.

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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.