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STARTING ON THE RIGHT TRACK: INTRODUCING STUDENTS TO MECHANICAL ENGINEERING WITH A PROJECT-BASED MACHINE DESIGN COURSE

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ABSTRACT

Over the past four years, we have redesigned Harvard's introductory mechanical engineering course to introduce the principles, practices, and pleasures of mechanical engineering in an accessible format. The main goals of the course are to provide experience in the design process, demonstrate the connection between engineering science and design early in the curriculum, and build student enthusiasm for engineering, serving to attract and retain students. Unlike most introductory mechanical engineering courses, we cover strength of materials and machine elements, material usually presented much later in the curriculum, in order to provide tools for the students to quantitatively evaluate their designs. By providing just enough of this background knowledge to allow for analysis of designs, we demonstrate the connection between engineering science and design early in curriculum and motivate in-depth coverage of these topics in later courses.

The laboratories for the course build enthusiasm for engineering by incorporating exciting design projects and introducing students to some of the most attractive mechanical engineering tools. Students learn 3-D solid modeling with CAD software, create prototypes from CAD models using manual and CNC machining, and reverse engineer common consumer products. Using these tools, students build their own hardware prototypes for both a cantilever beam catapult and a model all-terrain-vehicle. These exercises, carefully chosen to reinforce the strength of materials and machine elements concepts, culminate in design contests that enhance the visibility of engineering within the larger university community and increase student interest in the field.

Keywords: Introductory Mechanical Engineering Education, Freshman Machine Design, Problem-Based Learning, Innovative Curricula

INTRODUCTION

Training engineering students to be good designers is both an industry desire and an ABET stipulation [1, 2]. This fact has not gone overlooked in the academic community, and has frequently been addressed in the literature [3-6]. Curricular changes to provide a stronger emphasis on design education are happening, if slowly.

In a typical undergraduate sequence in mechanical engineering, students take an introductory design course in their first year, in-depth engineering science courses in subsequent years, followed by a capstone design course in the final year. There are a number of deficiencies with this sequence as it is frequently implemented. First, the introductory course is largely experiential, providing little training in engineering science and often failing to teach the proper engineering design methods [3, 6]. Students' lack of knowledge of engineering science precludes quantitative analysis of design alternatives, and the choice of design solution is based largely on intuition. Unsuccessful projects and discouraged students often result. Second, the capstone course often becomes the first time students connect their knowledge of engineering science to an open-ended design problem. A key motivator to retaining the material from course work is overlooked until after the fact.

To address these shortcomings, we have redesigned Harvard's introductory mechanical engineering course to introduce the principles, practices, and pleasures of mechanical engineering, especially design, in an accessible format. To guide the restructuring, we identified the following four programmatic goals:

- Provide both theoretical and applied experience in design process
- Demonstrate the connection between engineering science and design early in curriculum
- Build enthusiasm for engineering to attract and retain students
- Create visibility of engineering in the university community

In order to accomplish these goals, we employ active learning techniques to continually engage the students [7, 8]. A number of in-class group and individual exercises such as dissections of common consumer products [9] and brainstorming of design concepts complement lectures. These "highly active, low risk" activities make lecture material more interesting and appealing, and result in greater student learning [10, 11]. Laboratory work, which accounts for a large portion of students' time in the course, allows students to immediately apply the concepts presented in lecture and provides hands-on experience with the design process through individual and group projects [4, 12-14].

The course is structured around the process of machine design, which is an effective motivator for new engineering students. We provide a more rigorous introduction to engineering design than typical freshman-level design courses by introducing technical concepts typically covered much later in the curriculum [15]. These concepts are specifically chosen because of their exciting content and relevance to the design projects undertaken in the course [16].

Lecture topics consist of three main areas. The first set of topics concerns engineering graphics and computer-aided design. Students learn traditional drafting techniques as well as professional solid modeling CAD software [17, 18]. The second set of topics covers introductory strength of materials concepts. We discuss stress and strain due to simple uniaxial, torsional, and bending loads. Finally, we introduce interesting aspects of machine elements, such as motors, gears, and linkages. First-year students do not have the analytical background to understand this material in depth, of course, but these concepts are addressed later in the curriculum. However, with background in these more advanced engineering science concepts, we provide just enough knowledge for students to do simple quantitative analysis of their machine designs. This basic evaluation of design alternatives also motives the connection between design and analysis for upper level engineering courses.

Individual and group design exercises play a central role in the course. The first day of class is spent teaching design methodology [3, 6]. Students later learn first-hand how the design process works, including the roles of creativity, decision making, and group interaction. Two design projects are assigned, both culminating in exciting contests that build student enthusiasm [3, 19, 20]. These well-publicized events motivate students and enhance the visibility of engineering within the larger university community.

Work on the design projects is done primarily in the weekly laboratory sessions. Laboratory work is structured around many of the attractive aspects of mechanical engineering such as CAD software, CNC prototyping, reverse engineering of everyday consumer products, and experience with basic machine tools. Early laboratory sessions are focused on providing training and experience with these engineering design and fabrication tools. These skills are then tested in the two projects. The first, designed to reinforce the lectures on strength of materials, revolves around designing and fabricating a small, monolithic "catapult." In the second project, students design and build model all-terrain vehicles (ATVs) to compete on a carefully designed obstacle course.

Laboratory work in the course specifically links the theory presented in lecture to its implementation in hardware [5, 13]. These labs provide experience with modeling, creativity, design, and learning from failure - fundamental objectives of instructional laboratories as laid out by Feisel et al. (objectives 2, 7, 5, and 6, respectively [21]). The content of the labs was inspired in part by courses taught by Will Durfee at Minnesota [20] and Sheri Sheppard at Stanford [9], and has similarities to other courses described in the literature [17, 22, 23].

In the following sections we present an overview of the course material and a description of the laboratory projects, paying particular attention to the description of the final design project. We end with a discussion of the lessons we have learned from four years of student feedback and subsequent course revisions.

COURSE DESCRIPTION

Before presenting the specific content, it may be helpful to discuss the logistics of the course. Enrollment in the course is typically between 20-30 students, and is offered one semester per year. The course is very popular as an elective, both for other engineering students as well as non-majors. Approximately one-third of the enrollment over the past four years has been from students in fields other than engineering, with a number of students from humanities and social sciences.

Lectures consist of three 50-minute sessions per week, with a total of six problem sets assigned to reinforce the theory concepts presented. These account for 10% of the semester grade. Two one-hour, in-class exams are given, accounting for a total of 35% of the grade. Laboratory work, including design projects, accounts for the remaining 55% of the semester grade. Three-hour lab sessions are held weekly, and often involve pre- and/or post-lab exercises. Due to equipment and space constraints, lab sections are limited to 7 students, resulting in 3-4 total sections with a low student-teacher ratio. It is clear that the focus of the course centers on the labs and design projects.

Course material comes from three major engineering science areas: engineering graphics and design tools, strength of materials, and machine elements (Figs. 1,2). Material in these topic areas has been selected to provide students with enough background to allow quantitative analysis of their concepts for the two design projects. A more thorough understanding of the material is left for subsequent advanced courses. What follows is a description of the three topic areas, the laboratory sessions and teaching methods used to develop the desired skill sets, and a detailed description of the final design project (Fig. 3).

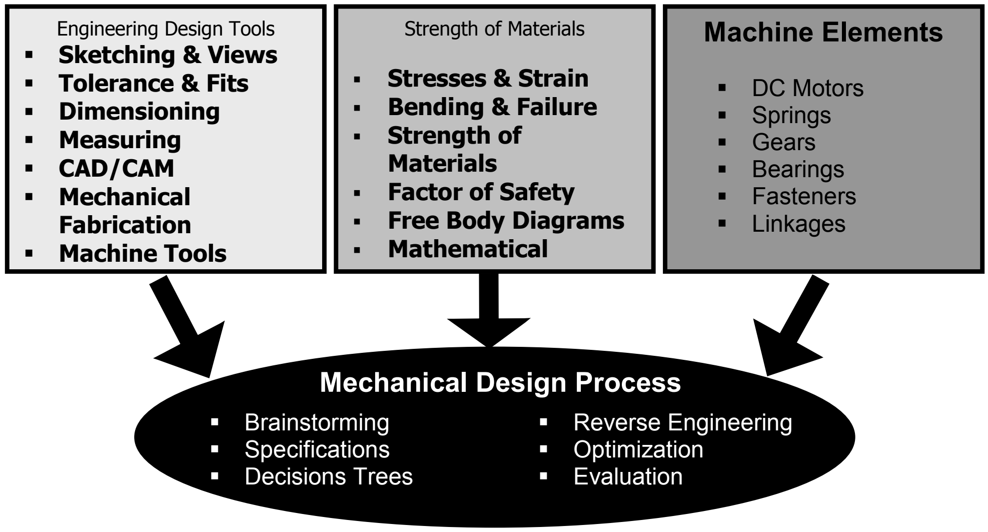


Figure 1: Course layout with topics of coverage

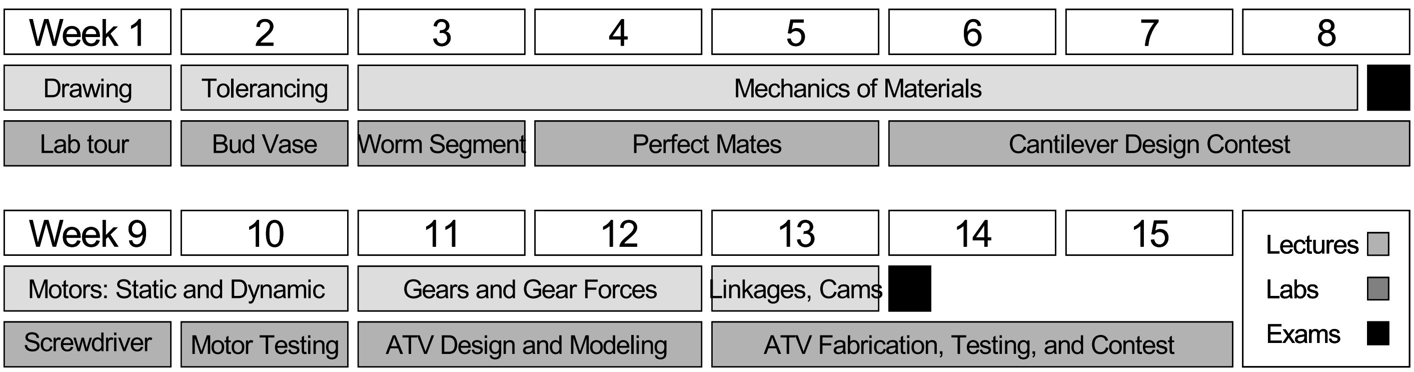


Figure 2: Course chronology with lab and lecture content

Engineering Design Tools

The first third of the course is dedicated to teaching students the tools required to effectively communicate and carryout their design ideas. In lecture, students are taught standard engineering graphics skills such as drawing and sketching techniques, orthographic and isometric views and projections, and dimensioning practices [18]. We pay particular attention to how tolerances and fits add up on parts with multiple features. Laboratory work is designed to give an intuitive understanding of how seemingly inconsequential differences in dimension result in vastly different interactions between two mating parts.

We also emphasize the importance of good laboratory practices, requiring students to maintain a design notebook. Students are expected to use their design notebooks for all laboratory sessions, group projects, calculations, sketches, and meeting notes, and are instructed on how to properly document their ideas and format their notebooks. These notebooks are periodically collected and graded throughout the course to emphasize their importance.

In the first of a number of dissection exercises, students dissect a videocassette tape as an in-class project, an exercise used by Will Durfee in his introductory engineering course at Minnesota [20]. Through reverse engineering, students obtain an appreciation for the highly varied forms and applications of simple machines, practice their sketching and measuring skills, and understand the importance of paying close attention to detail and careful note taking. A worksheet that accompanies the exercise asks questions that cause students to think deeper about the function and specifications of components of the assembly. Students are asked to estimate the clearance between mating parts, describe the function of certain mechanisms, and speculate about manufacturing and assembly methods. A take-home exercise forces the students to "think outside the box" by using engineering principles and intuition to come up with creative ways to estimate the length and thickness of the tape, complete with unit conversions and estimated error bounds.

The first three laboratory sessions are used to introduce students to mechanical fabrication. In the first session, students are introduced to proper shop procedure by building a small flower vase from acetyl tubes and acrylic plate. The lab begins with basic shop safety protocol and the proper use of common machine tools such as the drill press, band saw and taps. Students then prepare a part layout, designing the shape of the base and marking the tapped and through-hole locations on the

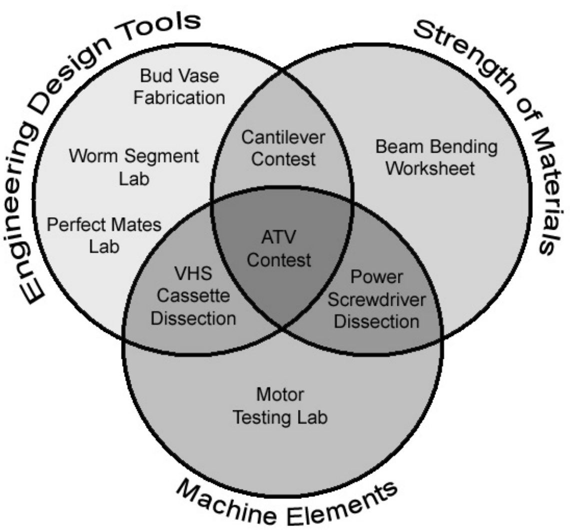


Figure 3: Integrating knowledge and application: Venn diagram of lecture and lab topics

base and tube. The remainder of the session is spent fabricating, assembling, and "finishing" their bud vases.

The second lab introduces students to milling and drives home the importance of accurate measuring, tolerance, fits, and dimensioning. The lab begins with instruction in the proper use of dial calipers and micrometers. They use these tools to accurately measure a small piece of rough-cut aluminum stock, paying attention to report their answers to the accuracy appropriate for the various instruments. They are then taught the basic procedure for use of a three-axis mill machine and are instructed to square the sides of the aluminum stock and bring it down to a specific dimension within a given tolerance. This simple task teaches the basics of milling terminology and practice: vice alignment, feeds and speeds, facing off, edge finding, and squaring edges, among others. They are then given a small steel dowel pin and are instructed to drill and ream holes for both a press fit and a clearance fit for the pin. This exercise reinforces the importance of careful measurement and design of tolerances and fits. Once the dowel pin is press fit into the block, the resulting assembly will mate with the clearance hole in their classmates' parts. The end result is a long chain of such segments that can rotate relative to one another in an interesting fashion, similar to the motion of a worm (Fig. 4).

The third engineering design tools lab is a two-session project intended to teach computer-aided design (CAD) and computer-aided manufacturing (CAM). Students use SolidWorks (SolidWorks Corporation, Concord, MA) to construct a model of a block containing required types of features that mate with features on their partner's block (Fig. 5). Students then use CamWorks (TekSoft CAD/CAM Systems, Inc., Scottsdale, AZ), a computerized numerical control (CNC) programming software package that integrates with SolidWorks, to generate machine code from this model. The parts are then CNC-machined from a high-grade machine wax (Freeman Manufacturing and Supply Co., Avon, OH), allowing for high feed rates and quick fabrication with little

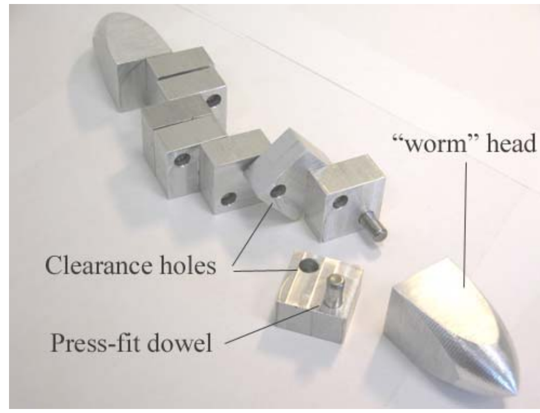


Figure 4: "Worm segment" with relevant features

tooling wear. The labs and associated lectures introduce students to the concept of design for manufacturing and design of tolerances and fits for assemblies, with the overall goal of understanding what features can and can not be machined.

Strength of Materials

During the second third of the class, the focus shifts to two classic introductory areas in engineering science, namely materials science and solid mechanics. We begin by teaching about the relevant materials properties that students must understand to compare and contrast materials for specific applications. Materials selection for performance optimization is then broadly covered with various added constraints such as geometric and cost considerations. The students are often surprised to learn how well natural materials like balsa wood can compete with modern hybrid materials such as carbon-fiber laminates in weight normalized strength under different loading conditions [24].

Next we cover stress and strain with specific attention toward beam bending theory. Reminding them that this lecture material will be essential to the upcoming catapult competition helps them to maintain focus. Lectures focus on loading conditions, uniaxial strain, shear forces, and torsion. Most importantly for the design project, force-deflection curves, potential energy storage in bending beams, and simple failure analysis, including fatigue loading and safety factors are introduced. More in-depth coverage of solid mechanics is left to subsequent courses, as our intent is to provide sufficient background for the design problems, and not a comprehensive curriculum in strength of materials.

In another in-class activity, we give students an opportunity to try out the strength of materials concepts. Students are given a bar clamp, ruler, spring scale, and thin rectangular bars of aluminum, acrylic, and PVC. At their desks with a partner, students use the provided equipment to determine the force-deflection curves of these materials, noting their different failure modes. Students repeat the exercise with different beam lengths, and relate the results to beam-bending theory.

This section of the course focuses on how material selection relates to the design process and why certain materials are selected given mechanical, manufacturing, and economic considerations. Our objective is to give the students the tools

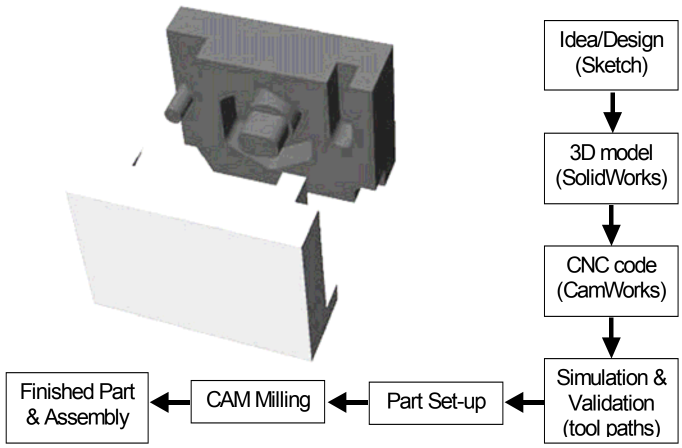


Figure 5: Process for “Perfect Mates” lab

they need as designers, requiring that their knowledge must work with the specification sheets they will review from manufacturers when making their own materials selections later in the course. The students need a working knowledge of aluminum numbering, steel grades, manufacturing methods and heat treatments for metals. They will need to understand the physical properties of polymers including yield stress, ultimate tensile strength, failure modes, dimensional stability and machinability. Most students are already aware of the importance of machinability issues after struggling to drill and tap brittle acrylic pipe for the first bud vase lab!

Cantilever Catapult Design Project

To apply material learned in lecture, and to build on concepts of engineering design tools, students spend three weeks in laboratory on a cantilever design contest. By applying beam-bending theory, students design a small, monolithic cantilevered beam device that performs some exciting task. Resulting devices are cantilevered beams optimized to store and return the most potential energy while meeting other constraints related to the design objectives. The initial implementation of this project involved designing a catapult to throw a small object as far as possible. We found that Tootsie Roll candies (Tootsie Roll Industries, Inc., Chicago, Illinois) worked well and added another entertaining dimension to the contest.

The first of three laboratory sessions is devoted to working through calculations and initial sketches for the catapult. This is one of the first opportunities for students to directly apply engineering science theory from the classroom to an open-ended design problem. Students utilize the material on solid mechanics and beam bending theory presented in lecture to design a beam that will be able to impart the largest amount of kinetic energy on to the projectile while paying attention to the object’s trajectory. However, students must pay careful attention to design restrictions related to dimensioning and material properties. Their device must fit snugly in the launcher base we provide as well as be completely contained within a specified area of the stock material (Fig. 6). Students must also consider mechanical constraints such as the yield strength and failure mode of the material. A selection of inexpensive plastic materials is provided, including polycarbonate, polyvinyl chloride, acrylic, high-density polyethylene, and polypropylene, from which the students must choose based on the provided material property data sheets.

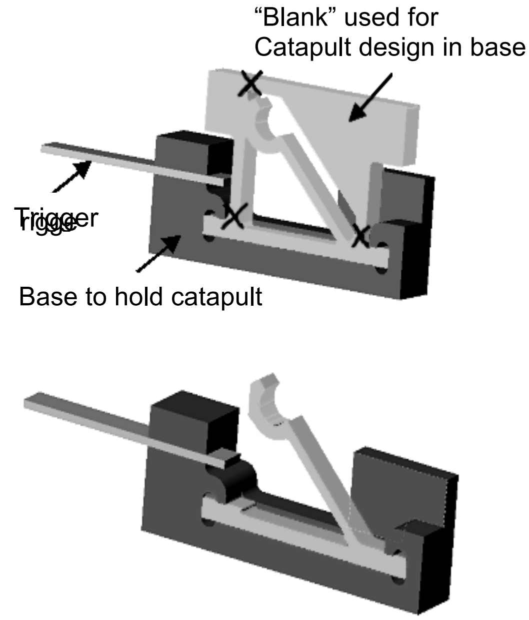


Figure 6: Catapult Cantilever Design Project. Top: Catapult design showing the “Blank” students had to design from. Bottom: Finished catapult with cuts made at “X’s” above.

The second week of the design contest is focused on developing a fully constrained CAD model in SolidWorks. As in the previous lab, students use CAM software to translate their computer models into G&M code to control 3-axis CNC mill machines. Students then fabricate their catapults using these machines. This session also serves to reinforce much of the machining skills learned in earlier labs.

The final week is left for redesign after careful evaluation of the performance of initial prototypes. At this point most students opt to create a second part, often of a different material. Some of the more competitive students attempt three or four iterations. The project ends with a class-wide contest where each student competes to catapult a projectile as far as possible, with a small prize going to the winner.

In order to slightly vary the project from year to year, successive contests are designed with different performance objectives for the beam device. Other implementations of the project include the “kung-fu cantilever”, in which students try to break as many small “bricks” as possible with their device, and “carnival cantilever”, where the objective is to design a “hammer” that can hit a ball to the top of a track and ring the bell.

This project’s integration of seamless design, analysis, and manufacturing allows students to take part in all steps of the design process and results in a rewarding educational experience [25]. In addition, the design contest helps to build enthusiasm for the course and mechanical engineering in general by giving students an open-ended problem where they can apply theory learned in lecture. It is the first time engineering students are taken through the design process from initial concept, sketching, solid modeling, prototyping, redesign, and final evaluation. Furthermore, a class-wide contest breeds competition and excitement, heightening student enthusiasm and interest in mechanical engineering and strengthening the sense of community among the students.

Machine Elements

Building upon students' understanding of basic engineering design tools and strengths of materials, the last third of the course focuses on machine elements. This section begins with an introduction to simple machines like the screw, gear, axel and wheel. Emphasis is placed on understanding gears, which will be an essential part of the all-terrain vehicle project. The gear lectures link strength of materials topics with static loading of gear teeth and axel torques. A bicycle is used to demonstrate gear ratio principles and to examine mechanical components in context. The mechanical disadvantage of typical bicycle gear ratios that are optimized for human speed-torque curves contrasts well the mechanical advantage required for most electric motor applications.

After gears, the next project-based essential knowledge topic for the students is small DC motors. While in lecture, the students learn about the electromotive force, commutation, windings and efficiency of DC motors. A laboratory series begins with dissecting and characterizing an inexpensive cordless screwdriver. The students experimentally measure the performance specifications of the screwdriver and then during disassembly create a detailed bill of materials. Certain parts must be measured to estimate tolerances used by the manufacturer and other parts must be sketched in multiple views.

This dissection exercise also allows students to apply their basic knowledge to develop an understanding of more complicated mechanisms. A significant challenge for students is to investigate and explain how the torque limiter works. Students are also fascinated by the how a large gear ratio is achieved with the multi-stage planetary gear head. And the electrical circuit that provides for forward and reverse direction operation of the screwdriver is sufficiently challenging to perplex even the brightest students unless they learn to draw an electrical schematic.

We also require students to make observations about design for manufacturing and to consider what cost-saving measures have been incorporated in the design of the screwdriver. It is astounding how such a complicated machine can be manufactured and sold for less than the cost of a pepperoni pizza!

The next laboratory session is devoted to characterizing the electromechanical properties of the DC motors, with the purpose of producing a motor specification sheet to a level of detail similar to those provided by a manufacturer. In the process of measuring properties such as the no-load speed, stall torque, and voltage and torque constants, students are introduced to the use of oscilloscopes, voltmeters, and tachometers (by way of an emitter/detector phototransistor pair). Since the students are never provided the "true" motor specifications, they must rely on their own characterization for later use in design.

As students are introduced to their final design project, lectures continue to complete topics in machine elements by covering cams and linkages. In keeping with the vehicle theme of the final project, examples are drawn from automotive engines, windshield wipers, and steering systems. Most

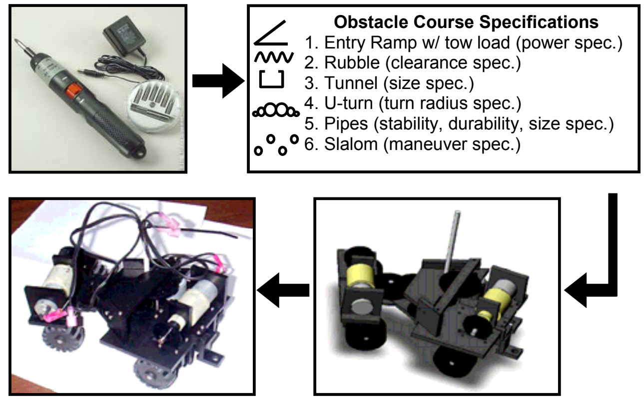


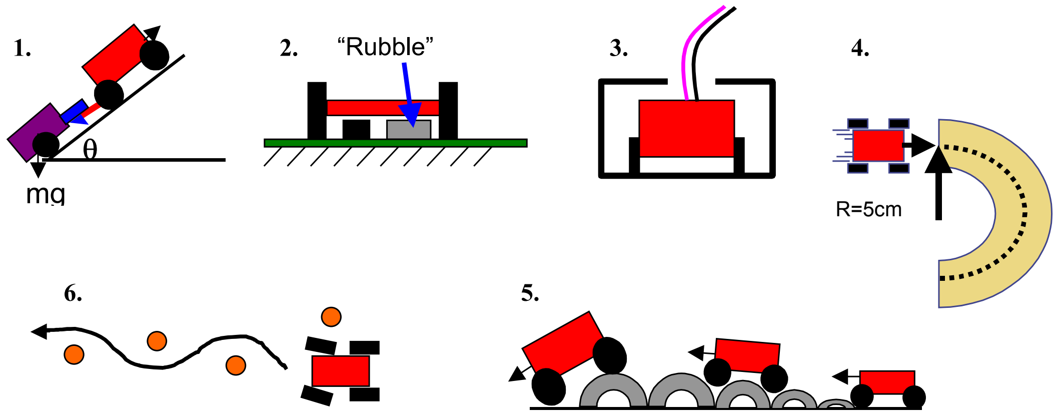
Figure 7: ATV lab process: base components, performance specifications, solid model, and prototype

students will not actually use cams and linkages in their final design project and so there is no pressure to complete this lecture series prior to beginning project design work. To complement the early stages of the final design project, students are given more elaborate design tools in special lectures on brainstorming and prototyping using foam-core poster board.

Final Design Project

The final lab in the course is a culminating event where nearly all of the engineering content must be applied in service of the underlying programmatic goals of the course. Students work in teams of 3 or 4, assigned by the teaching staff to create groups with an even distribution of talented and experienced students [26, 27]. The groups work to transform the power screwdrivers they previously dissected, the motors they previously characterized, and some additional parts into an all terrain vehicle (ATV) (Fig. 7). The student groups then publicly compete with their ATV's on a challenging obstacle course. The design of the ATVs is driven by the performance, design, and manufacturing requirements that are outlined for the students in detail. Winning designs are creative, well built, maneuverable, and have the right balance of speed and torque.

The essential design challenge of the lab is to use the power screwdriver motors with gears, shafts and a CAD/CAM/CNC manufactured acetyl chassis to implement drive and steering systems. The design process is partially constrained by the provided tools, materials and small spending budget ($50 per group has worked well). More significant, however, are the performance-based design constraints enforced by the layout of the obstacle course (Fig. 8). For example, the course begins with the requirement that the ATV tows a 5-kilogram trailer up a 30-degree incline ramp from the floor to the tabletop course. The gear ratio on the motor must be sufficiently high to produce enough towing force for the task, but an overly high gear ratio would result in a slow drive speed once the trailer is unhitched at the top of the ramp. Rather than prescribe a specification, we let the students weigh the trailer, measure the ramp, and compute an optimal gear ratio based on the engineering science they have learned. Students sometimes overlook important specifications such as the friction between the wheels and the ramp surface or hitch location relative to the ATV wheelbase and center of mass. These situations create



Task	Name	Objective	Performance Specification
1	Incline Load Pull	Go up a ramp onto course towing a 5 kg trailer. Unhitch trailer at top.	Power, Maneuverability
2	Rubble Field	Traverse over circuit-board rubble.	Clearance
3	Tunnel	Travel through a “tunnel” that will have a slot on the top for the tether.	Size, ability to drive straight
4	U-turn	Change direction on the course.	Turning radius
5	Bumpy Bridge	Climb-up onto the horizontal pipes, drive over them, and drop-off the other side.	Power, clearance, durability
6	Slalom Course	Complete the slalom course.	Maneuverability

Figure 8: ATV lab obstacle course description with performance specifications

teachable moments in the lab when teaching assistants can help guide the students through difficult design changes.

A recurrent theme of the ATV lab is how it builds on previously acquired knowledge. This not only applies to the engineering science content, but also to the results of previous laboratory experiments. A good example of this is how the students must rely on the specifications gained from reverse engineering the screwdriver and its motor. There is also significant progression in the skills acquired for the computer-aided design and manufacturing activities. The level of complexity of the ATV in a SolidWorks assembly is such that good planning and experience is a requirement for success. The students use their acquired knowledge of manual prototyping, tolerances and fits, materials properties and mechanics, machine elements, kinematics, fasteners, manufacturing constraints, elementary circuits and more. A level of proficiency in all of these areas is required in the context of a structured design process or the ATV simply will not be completed on time and will not work.

In order to prevent complete failure of a specific design and encourage students along the way, we implement a few milestone checkpoints throughout the process [28]. The first of these comes before students begin creating the SolidWorks model of their designs, where the teaching staff checks the foam-core prototypes for factors such as stability, ease of manufacture, and reasonable gear ratio. During these design evaluations, we take a “teacher as manager” approach, acting as a source of design expertise and otherwise not involved in the decision-making process [28]. The second checkpoint comes closer to the contest deadline, where students must demonstrate a working gear train with sufficient time remaining to address any serious mechanical issues.

A great deal of spontaneous peer-to-peer instruction of course content occurs in the student teams as a result of the practical challenges of this project. These types of interactions are highly desirable and have been shown to significantly increase student learning [27, 29]. Working in groups also results in better performance than individual work and builds relationships that can help build the community of engineers [27].

We hold the final competition for the ATV lab in a stadium style auditorium with overhead video projected on a screen and stage lighting. Advertisements are posted around campus and faculty and administrators are encouraged to attend. The competition is an opportunity for the engineering students to shine! The CAD renderings of the ATVs are projected onto the screen as the groups are introduced to a cheering audience. Before competing, student groups are required to describe their vehicle and justify their design choices to the audience. The actual competition naturally develops nail-biting excitement as some groups succeed beautifully while others experience mechanical failures that they attempt to fix while the clock runs down. Point counts are called out as they are accumulated and written on the blackboard and a token “grand prize” is awarded to the winning team. The excitement of the final competition is highly visible (and audible) in the university community and has become a talked-about event on the academic calendar. This is exactly the sort of publicity that can help to attract students to the field.

DISCUSSION

Engaging students in a project-based machine design course early in their undergraduate careers starts them on the right track in mechanical engineering. Our course employs computer-aided design to reduce the time and training required for the students to fully experience the engineering design process from conceptualization to function. Students learn how the design process works, including the roles of creativity, decision-making and group interaction, and a series of design contests build student enthusiasm. Through careful selection of projects, the course builds sequentially upon accumulating knowledge and skills leading to a final integrated design project that culminates in a well-publicized competition. As a result of these attributes, students receive a more rigorous introduction to mechanical engineering design than in typical freshman-level design courses while having lots of fun. This is a formula that works to attract, retain and educate engineers [3, 16, 30].

Our experience with this course has reinforced three guiding principles essential to reaching our intended goals. First, it is essential to choose a subset of mechanical engineering curriculum that forms a cohesive unit and is accessible to students with little background in the field. We settled on the particular combination of engineering design tools, strength of materials, and machine elements after some tuning over the years. These topics are both exciting and work well when presented concurrently in the lectures and labs. With background in these more advanced concepts, we are able to educate students in the entire design process, allowing for the quantitative analysis of design alternatives that is not possible in traditional introductory courses. Additionally, by demonstrating the utility of engineering theory in design problems to freshman, students are better motivated to absorb and apply material learned in junior and senior level courses.

The second guiding principle is to broadly incorporate creativity in the course within appropriately constrained design projects. We find that there is a balance to strike when posing a design problem for students who are engineering novices. While overly constrained projects can be dull and boring for many students, too much creative license does not guide them to apply engineering science in intended ways nor in the successful completion of their projects.

Finally, we find that the human element in competition breeds excitement and increases student interest in the course and major. Friendships from shared trials and tribulations in the design projects are an essential factor in engaging intelligent and talented engineering students and strengthening the engineering community within the university.

Perhaps the comments we have collected from the students of the last four years best sum the successes of the course:

"[The bud vase lab] was a cool way to start off, you get an immediate rewarding thing that you made."

"[The ATV lab] was awesome. I loved the design aspect, the minimal constraints on the design, and the creativity involved. I think the creative stuff was really important although the more technical knowledge is necessary. That's why I liked the ATV lab so much."

"The labs made me want to do [engineering] more."

"I now know how to calculate structure values and build cool stuff. The course is interesting and engaging and the subject is useful and practical."

"I would recommend [this course] to any engineer. This is what it's all about. If you don't like this course, engineering is not for you."

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REFERENCES

[1] "Engineering Criteria 2000," Engineering Accreditation Commission of the Accreditation Board for Engineering and Technology 1996.

[2] McMasters, J. H. and Matsch, L. A., 1996 "Desired Attributes of an Engineering Graduate - An Industry Perspective," 19th AIAA Advanced Measurement and Ground Testing Technology Conference, New Orleans, LA.

[3] Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., and Leifer, L. J., 2005 "Engineering Design Thinking, Teaching, and Learning," *Journal of Engineering Education*, vol. 94, pp. 103-120.

[4] Ditcher, A. K., 2001 "Effective Teaching and Learning in Higher Education, with Particular Reference to the Undergraduate Education of Professional Engineers," *International Journal of Engineering Education*, vol. 17, pp. 24-29.

[5] Brereton, M., Sheppard, S., and Leifer, L., 1995 "Students Connecting Engineering Fundamentals and Hardware Design: Observations and Implications for the Design of Curriculum and Assessment Methods," Frontiers in Education, Atlanta, GA.

[6] Devon, R., Bilen, S., McKay, A., Pennington, A. D., Serrafero, P., and Sierra, J. S., 2004 "Integrated Design: What Knowledge is of Most Worth in Engineering Design Education," *International Journal of Engineering Education*, vol. 20, pp. 424-432.

[7] Kazmer, D. O., 1998 "On the Divergence of Case Studies and Hardware Prototypes in Active Learning," ASEE Northeast Regional Meeting, Amherst, MA.

[8] *Speaking of Teaching: The Stanford University Newsletter on Teaching*, 1993 "Active Learning: Getting Students to Work and Think in the Classroom," vol. 5.

[9] Sheppard, S., Mechanical Dissection, Department of Mechanical Engineering, Stanford University.

[10] Demetry, C. and Groccia, J. E., 1997 "A Comparative Assessment of Students' Experiences in Two Instructional Formats of an Introductory Materials Science Course," *Journal of Engineering Education*, vol. 86, pp. 203-210.

[11] Bonwell, C. C. and Eison, J. A., "Active Learning: Creating Excitement in the Classroom," The George Washington University, School of Education and Human Development, Washington D.C. ASHE-ERIC Higher Education Report No. 1, 1991.

[12] Liu, Z. E. and Schoenwetter, D. J., 2004 "Teaching Creativity in Engineering," *International Journal of Engineering Education*, vol. 20, pp. 801-808.

[13] Harris, D., 2001 "A Case for Project-Based Design Education," *International Journal of Engineering Education*, vol. 17, pp. 367-369.

[14] Graaff, E. D. and Kolmos, A., 2003 "Characteristics of Problem-Based Learning," *International Journal of Engineering Education*, vol. 19, pp. 657-662.

[15] Poinke, C. D., Parsons, J. R., Seat, J. E., Weber, F. E., and Yoder, D. C., 2001 "Balancing Capability, Enthusiasm and Methodologyin a First-Year Design Program," *International Journal of Engineering Education*, vol. 17, pp. 381-385.

[16] Yokomoto, C. F., Rizkalla, M. E., and O'Loughlin, C. L., 1998 "A Successful Motivational Freshman Design Experience Using Attached Learning," Frontiers in Education Conference, Tempe, AZ, pp. 493-499.

[17] Hirose, S., 2001 "Creative Education at Tokyo Institute of Technology," *International Journal of Engineering Education*, vol. 17, pp. 512-517.

[18] Barr, R. E. and Juricic, D., 1994 "From Drafting to Modern Design Representation: The Evolution of Engineering Design Graphics," *Journal of Engineering Education*, vol. 83, pp. 263-270.

[19] Slocum, A. H., Design and Manufacturing I, Department of Mechanical Engineering, Massachusetts Institute of Technology.

[20] Durfee, W. K., Introduction to Engineering, ME2011, Department of Mechanical Engineering, University of Minnesota.

[21] Feisel, L. D. and Rosa, A. J., 2005 "The Role of the Laboratory in Undergraduate Engineering Education," *Journal of Engineering Education*, vol. 94, pp. 121-130.

[22] Chan, V. H., 2004 " Learning CAD/CAM and CNC machining through minicar and catapult projects," *International Journal of Engineering Education*, vol. 20, pp. 726-732.

[23] Elata, D. and Garaway, I., 2002 "A Creative Introduction to Mechanical Engineering," *International Journal of Engineering Education*, vol. 18, pp. 566-575.

[24] Ashby, M. F. and Jones, D. R. H., *Engineering Materials 1: An Introduction to their Properties and Applications*. Oxford: Butterworth-Heinemann, 1980.

[25] Beuth, J. L., 1997 "Integration of Seamless Design, Analysis and Manufacturing Concepts into Undergraduate Mechanics Courses," Frontiers in Education Conference, Pittsburgh, PA, November 5-8, 1997.

[26] Hunkeler, D. and Sharp, J. E., 1997 "Assigning Functional Groups: The Influence of Group Size, Academic Record, Practical Experience, and Learning Style," *Journal of Engineering Education*, vol. 86, pp. 321-332.

[27] Johnson, D. W., Johnson, R. T., and Smith, K. A., 1998 "Maximizing Instruction Through Cooperative Learning," *ASEE Prism*.

[28] Delson, N. J., 2001 "Increasing Team Motivation in Engineering Design Courses," *International Journal of Engineering Education*, vol. 17, pp. 359-366.

[29] Felder, R. M. and Brent, R., 2001 "Effective Strategies for Cooperative Learning," *Cooperation and Collaboration in College Teaching*, vol. 10, pp. 69-75.

[30] Anderson-Rowland, M. R., 1997 "Understanding Freshman Engineering Student Retention Through a Survey," American Society of Engineering Education Conference, Milwaukee, WI.