AC 2007-2496: EDUCATING BY DESIGN: TEACHING NON-ENGINEERING MAJORS TO DREAM

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Abstract

In recognition of some of the challenges involved in teaching engineering to students whose academic leanings are away from math/science fields, ME450 was developed at the United States Military Academy (USMA) to provide a comprehensive, integrated engineering experience to students enrolled in humanities, social sciences, life science and other non-engineering degree programs. Lessons learned through the development and implementation of this course may be applicable to programs seeking to expand or develop minors in engineering or provide challenging and rewarding experiences in design-based courses to students who might otherwise be reluctant to explore this potentially demanding and work-intensive field.

Introduction

“All people dream, but not equally. Those who dream by night in the dusty recesses of their mind wake in the day to find that it was vanity. But the dreamers of the day are dangerous people, for they may act their dream with open eyes to make it possible.”

—T. E. Lawrence

How do you teach students who do not want to be taught? The answer to the question is a critical one, particularly as universities begin to incorporate more broad-based core curricula into their academic programs in order to produce graduates equipped to meet the challenges of an increasingly technologically oriented world. The overarching goal of the United States Military Academy’s academic program is to enable its graduates to anticipate and respond effectively to the uncertainties of a changing technological, social, political, and economic world. To this end, graduates are expected to demonstrate proficiency in six key domains:

- Engineering and Technology
- Math and Science
- Information Technology
- History
- Culture
- Human Behavior

Exposure to all of these domains provides students with a valuable appreciation for how each discipline deals with the gathering and processing of knowledge. While it is not uncommon to require engineering students to take basic courses in history, humanities and social sciences, the converse is not typically true. Because of this, Universities that recognize the need to expose undergraduate students to technology-based courses should anticipate challenges as these types of courses become graduation requirements for students who would otherwise choose not to take them.
At USMA, the objectives of the non-engineering technical curriculum go beyond providing a cursory introduction to information technology. Developing an understanding of how engineers apply problem-solving methodologies to address real-world, open-ended problems is a fundamental objective of the Academy’s academic program so, after receiving six credit hours of basic IT instruction, students are required to take an additional 3 semester-long engineering courses from one of the Academy’s eight engineering programs. It is a requirement that the third course accomplish USMA Engineering and Technology goals by providing an integrating experience that challenges students to apply principles and theory learned during the previous two semesters to design-based coursework. The mechanical engineering sequence, although regarded by students to be one of the Academy’s most academically rigorous offerings, has been successful in generating significant enthusiasm and positive student feedback through the unique methods by which learning opportunities are provided by the third and final course, ME450.

The key element of success is embodied in the presentation of mechanical engineering design as an art form: an art which, by its very nature, provides the artist with the ability to synthesize and create something from nothing; to develop solutions to seemingly unsolvable problems; to, literally, provide the student with the ability to dream his or her dreams into reality.

Challenges

“What do I expect to get out of ME450? No sleep and less free time—and not much else!”

—Political Science Major, Prior to ME450 Lesson 1

You would be hard-pressed to begin with a group of students less excited and more unwilling to learn about mechanical engineering than those who were enrolled in ME450 at the start of the fall 2006 semester. Initial entry surveys recorded responses such as “I did not select the ME program. It was my sixth choice out of eight,” and “I didn’t choose ME, I was forced to take it,” to the question, “Why did you choose mechanical engineering as your sequence?” All of the almost one hundred students enrolled in ME450 had taken statics and strengths of materials and thermo-fluids over the previous two semesters, and the experience for these predominantly language, history, and social science majors had resulted in the development of four generalized attitude groups, loosely identified by responses provided in their initial entry surveys: the first group was composed of students who had come to the conclusion that engineering was next to impossible to understand, much less excel in. These students were discouraged by difficulties they had experienced and intimidated by the prospects of another semester of engineering instruction. The second group was typically composed of students who had been forced to take the mechanical engineering sequence and, regardless of their previous performance, had made up their minds that engineering was irrelevant, both to their academic interests and to their future careers. The third group was made up of students who had agreed to sign up for the mechanical engineering sequence due to a merely casual interest in mechanical systems, or a vague idea that engineering was somehow related to building things. Their motivation to learn outside of their academic “comfort zones” was low, and their tendency to tune out when presented with difficult or challenging concepts was high. The fourth (and smallest) group consisted of students who were genuinely excited by the engineering courses that they had taken so far, and eager to take
advantage of an opportunity presented to apply some of the theory and tools to which they had been exposed during their first two engineering courses.

The course objectives of ME450 are tied directly to the USMA Engineering and Technology goals, shown below. These goals are comprehensive, incorporating all six elements of Benjamin Bloom’s taxonomy of educational objectives. The ambitious nature of these goals is amplified in ME450 by the general lack of engineering background and “attitude demographics” of the enrolled students.

United States Military Academy Engineering and Technology Goals

Upon successful completion of the engineering sequence, students should be able to:

1. Identify a need that can be fulfilled via an engineered solution.
2. Define a complex technological problem, accounting for its political, social, and economic dimensions.
3. Determine what information is required to solve a technological problem; acquire that information from appropriate sources; and, when available information is imperfect or incomplete, formulate reasonable assumptions.
4. Apply the engineering design process and use appropriate technology to develop solutions that are both effective and adaptable.
5. Demonstrate creativity in the formulation of alternative solutions to a technological problem.
6. Apply mathematics, basic science, and engineering science to model and analyze a physical system or process; and apply the results of that analysis to the solution of a technological problem.
7. Work effectively as a member of a team to solve a technological problem.
8. Plan the implementation of an engineering solution.
9. Communicate an engineered solution to both technical and non-technical audiences.
10. Assess the effectiveness of an engineered solution. Demonstrate basic-level technical proficiency in an engineering discipline.
11. Demonstrate basic level technical proficiency in an engineering discipline.
12. Learn new concepts in engineering and new technologies without the aid of formal instruction.

In recognition of the potential obstacles to learning posed by the disparity between course objectives and students’ perceived abilities and academic interests, ME450 was deliberately designed to provide instructors with opportunities to break down barriers to learning and present lesson material in ways that would evoke curiosity and interest in even the most reluctant would-be engineers.

Methodology

Figure 1 below illustrates Joseph Lowman’s generic depiction of the various sources of influence on college student learning:
Given the unique dynamics created by a combination of the relatively low student ability and motivation and the exigent nature of course objectives, a revised representation of Lowman’s model (Figure 2) was developed to represent the teaching strategy adopted by ME450 instructors.

Figure 1: Sources of Influence on College Learning

Figure 2: Diagram of Revised ME450 Student Learning Model
As indicated by this model, ME450 relies on organized, high-energy classroom activities, challenging individual assignments and group projects, and frequent opportunities for assessment and feedback to create an environment in which students can come to enjoy the task of learning the fundamentals of engineering design. The criticality of identifying the overarching course objective as developing and enhancing problem solving skills cannot be overemphasized. The effective communication of this intrinsically relevant objective was essential to gaining student interest and building motivation to learn and apply concepts presented in the course. The practice of consistently presenting each lesson within the context of its relationship to the ultimate goal of enhancing problem solving skills resulted in an overwhelmingly positive student perception that well-articulated lesson objectives and course structure contributed heavily to their ability to learn course material. The value of instructor ability and motivation, while also identified by students as making a significant positive contribution to the learning environment, varies greatly with teacher experience and personality, and will therefore not be addressed within the scope of this paper.

**ME450 in the Classroom**

The principles governing the design of a familiar mechanical system, the Army’s Medium Armored Vehicle, were examined in depth during the first 10 lessons of the course, during which time students were given the opportunity to apply these principles and “redesign” the system using the initial problem statement as a starting point. The results of their design process were then presented in a side-by-side comparison with actual performance specifications of the system in order to allow the students to imagine the relative advantages and disadvantages of the system as they had designed it. This confidence-building exercise also served to provide continuity in the classroom, as each lesson built progressively on the foundation of the previous lessons.

As often as possible, classroom lectures were structured around open discussions which served as a vehicle to teach students that their input, however inexperienced or uninformed, was valid. In many cases, these discussions allowed students to demonstrate unique opinions or uncommon knowledge that they possessed, further enhancing the positive nature of the experience. Selections from a very easy to read, non-technical text, Patrick Dym and Clive Little’s *Engineering Design*, were used as the basis for lively in-class discussions, during which students were encouraged to cite examples of the concepts discussed from their own experience, and challenged to imagine applications for relevant principles in the world around them. For example, to facilitate a better understanding of customer objectives and design functions, students were asked to list the reasons why they selected the cars that they were currently driving, and then relate these desires to quantifiable performance measures (passenger capacity, fuel economy, acceleration, etc). The resulting discussion served to effectively illustrate the relationship between objectives and functions, thus illuminating one of the most fundamental concepts governing engineering design.

As the course transitioned to more technical material, innovative demonstrations and physical models were used to provide concrete illustrations of abstract principles. The effect of the relationship between center of gravity and center of pressure on rocket dynamics was shown by firing various deficient (and one properly designed) air-powered rockets at the likeness of the United States Naval Academy’s mascot. A model tractor pull, complete with cheering sections
composed of designated students, was used to illustrate the interaction between torque, power and traction in producing propulsive force in a vehicle. These energetic presentations were not only fun to deliver, they were extremely effective at eliciting student enthusiasm and participation, as demonstrated by a 96 percent positive response to the end-of-course student survey statement, “My instructor used visual images (pictures, demonstrations, models, diagrams, simulations, etc.) to enhance my learning.”

Assignments and Projects

Although classroom activities were constantly used to emphasize the fact that engineering design is simply an organized, methodical approach to problem solving, this message was most effectively communicated through the frequent incorporation of tangible experiential activities designed to emphasize the real-world applications of engineering theory and, most importantly, competitive team-based engineering design projects. Hands-on exercises such as a welding lab (see Figure 3) in which students were given the opportunity to test the strength of their MIG-welded steel specimen against that of a specimen welded by their instructor and a geartrain lab in which students were challenged to build the most efficient LEGO™ geartrain possible, given specific constraints, were frequently cited by students in the end-of-course survey as highlights of their learning experience. These activities had the effect of helping students relax and enjoy the class in a way which, according to one history major, “almost made me forget I was learning about engineering.”

Another assignment that successfully developed student excitement for the real-world applications of engineering design was a short presentation that each student was required to make on a developing technological system of their choice. During this presentation, students identified elements of the engineering design process that had influenced characteristics of the final (or prototype) product, and made recommendations for further improvement based on their understanding of customer objectives and critical product functions. Students consistently reported that the exercise provided them with a heightened appreciation for the presence of elements of methodical design in the world around them. To further enhance this appreciation, the course incorporated a visit to the Army’s Armament Research, Development and Engineering Center.
Students were provided firsthand exposure to cutting-edge advancements in technology as they observed the application of engineering science to emerging real-world requirements (see Figure 4). This trip was universally acknowledged as one of the best experiences of the course; a time during which, in the words of one student, “all the pieces started to come together, and I saw how engineering really works.”

The core of ME450 was based on three unique engineering design projects, or EDPs, that served as the vehicles to provide students the opportunity to practice taught principles and receive performance-based feedback on their ability to successfully synthesize and apply course material. Although the use of design projects to teach and emphasize principles of engineering design is common fare in most engineering courses, the unique way in which the ME450 design projects were structured and introduced were critical to sparking student interest and building student motivation to perform. Wankat and Oreovicz, in *Teaching Engineering*, identify several different methods of classifying design projects, based on some of the following relative scales:

- Serious versus fun
- Theoretical (or “paper”) design versus hands-on
- Structured versus open-ended
- Individual versus group
- Simple versus complex

Each EDP’s classification with respect to these scales appears in Figure 5:

![Figure 5: EDP Classification](image)

The first EDP presented in ME450 was carefully crafted to begin at the left-hand side of the scales, allowing students to focus their learning almost exclusively on understanding and applying principles of design on the first assignment, a “paper design” of a field-expedient shower facility. This project relied heavily on theory taught during the previous semester’s thermo-fluids course and was limited in scope, with clearly-defined constraints and objectives. The initial phases of this project were assigned as individual graded requirements, accomplishing the dual purpose of allowing students to accrue points on individual merit while providing instructors with the opportunity to assess each student’s unique strengths and weaknesses. The second project, the design of a water bottle rocket, introduced new concepts of basic aerodynamics, which students were required to understand and apply in order to develop a product to meet design objectives that were only loosely defined by the initial problem statement. Students were required to evaluate the relative importance of performance specifications outlined in the problem statement in order to determine which objectives to focus
their efforts on achieving. The concept of design compromise was introduced in this moderately challenging EDP. Students were assessed not only on their ability to exercise the engineering design process, but also on the performance of their final design in real-world competition. Working in design teams, students were required to fabricate their concepts and launch them to assess rocket accuracy and payload capacity (see Figure 6). As scores were based on performance relative to other student design teams, as well as to an objective standard, motivation to excel was extremely high throughout the course.

The final EDP, the culmination or “capstone” project, was deliberately designed to fall along the extreme right of every one of the scales, leveraging the anticipation of an extremely fun project to build excitement and enthusiasm for what would prove to be a significantly challenging engineering problem. Students were tasked to develop prototype unmanned vehicles to conduct a series of complex tasks, using LEGO™ components and a three-channel wireless electric control module. As with the second EDP, the final performance assessment would be competition-based. However, the stakes were raised significantly by the introduction of a single-elimination tournament that would pit each design group’s solution against another’s in head-to-head competition. This course-wide competition, which took the place of a final exam, received high praise from students due to the excitement that it created. “[This competition] really gave me something to look forward to and work towards,” stated one student, commenting on his team’s performance in the final round of the tournament (see Figure 7).

Feedback and Assessment

The final component of the ME450 teaching model is a robust two-way feedback loop that allows instructors to provide frequent and timely assessments to guide student learning while continuously providing a mechanism for students to communicate their concerns and identify possible sources of confusion before becoming overwhelmed. Methods for accomplishing this over the course of the semester included the use of informal classroom surveys, internet instant messaging, formal in-progress reviews, and an extremely short response time on all graded student submissions. In order to ensure that the course continues to evolve and gain effectiveness at accomplishing its objectives, several different methods of course assessment were incorporated into the final events of the semester.
During class, instructors made periodic use of informal survey methods such as the “muddiest point paper,” in which students were required to write down, in one minute or less, the concept presented in the past few lessons which was most unclear or confusing to them. Results of this survey were collated and presented to students in the following class period. Based on the topic, efforts were made to address confusion immediately or incorporate additional instruction into future lectures as appropriate. This method of soliciting feedback was not only successful in helping to identify and address potential conceptual problem areas within the course, it also communicated the priority placed by instructors on student learning. Another useful method of facilitating two-way communication between instructors and students was the use of internet instant messaging to receive and answer the last-minute questions which invariably arose the night before major graded assignments were due. By establishing a discreet “contact window” in the evenings before submissions, instructors were able to make themselves available to students, using a non-threatening and extremely common method of student communication. The effectiveness of both of these feedback techniques was evidenced by the overwhelming student assessment of ME450 instructors as concerned with individual student learning.\footnote{8}

An additional feedback mechanism, the in-progress review, or IPR, was incorporated one to two times within the course of each EDP. This event, which involved students briefing their instructors on project status, with the instructor playing the role of client, provided students with opportunities to hone their communication and presentation skills. At the same time, these IPRs allowed instructors to give a personalized assessment of individual and design team’s success at understanding and incorporating principles of engineering design into their projects. Conducted in this manner, the IPRs effectively strengthened student-instructor relationships while ensuring that student efforts were regularly commended, encouraged, or re-focused, as needed. A second method of providing academic guidance and direction was the timely return of all graded assignments, typically during the lesson following the assignment’s submission. Assignments in ME450 were always returned with detailed expository instructor comments as well as a numerical score. This explanatory aspect of evaluation, as Lowman points out, maximizes student learning by indicating the care with which the assignments were read, reinforcing good performance and demonstrating a genuine concern that students understand the reasons for poor performance.\footnote{9}

The final means of facilitating student-instructor communication in ME450 came through a robust end-of-course assessment procedure that involved in-class discussion combined with the completion of an extensive online survey and the submission of reflective essays which covered student impressions of the positive aspects of the course, along with recommended areas for improvement. Data gathered from these surveys and essays has been extremely valuable in assessing the effectiveness of ME450 as a vehicle to provide the fundamentals of an engineering education to students in non-engineering majors.

\textbf{Results}

The primary mode of obtaining an objective assessment of the efficacy of ME450 in accomplishing USMA’s Engineering and Technology goals is provided by end of course survey data. This data, compiled from an online survey taken by students immediately following the final lesson and presented in Figure 8, provides insight into which Engineering and Technology
goals are best served by the content and format of the course. With an average of over 90 percent of the total number of enrolled students responding that they either “agree” or “strongly agree” that ME450 enabled them to achieve all 12 USMA Engineering and Technology goals, the course could easily be considered a success in a purely quantitative sense. The lowest score given by students was attributed to goal number six, the ability to apply math and basic science to model and analyze a physical system. With respect to this goal, 50 percent of students enrolled agreed that their abilities had improved, while only 35 percent of students “strongly agreed” that their abilities had improved. This result is understandable, as the course relies heavily on a student’s ability to understand and synthesize material from courses taken in previous semesters in both the physics and the engineering departments. The teaching of new technical material is kept to a minimum, with the emphasis being placed on developing the student’s ability to effectively apply the engineering design process to develop solutions to real-world problems. By the same token, the relatively high score in both “ability to work effectively as a member of a team to solve a technological problem” (55 percent “strongly agreed” and 40 percent “agreed” that their ability had improved) and “ability to plan the implementation of an engineered solution” (51 percent “strongly agreed” and 42 percent “agreed” that their ability had improved) is not surprising in a course that is structured around the presentation and application of the engineering design process.

Figure 8: End of Course Survey Data for ME450

1. Identify a need that can be fulfilled via an engineered solution.
2. Define a complex technological problem.
3. Determine what information is required to solve a technological problem.
4. Apply the engineering design process to develop effective, adaptable solutions.
5. Demonstrate creativity in the formulation of alternative solutions.
6. Apply mathematics, basic science, and engineering science to model and analyze a physical system or process.
7. Work effectively as a member of a team to solve a technological problem.
8. Plan the implementation of an engineering solution.
9. Communicate an engineered solution.
10. Assess the effectiveness of an engineered solution.
11. Demonstrate basic level technical proficiency in an engineering discipline.
12. Learn new concepts in engineering and new technologies without the aid of formal instruction.
The best indication of the success of ME450’s hands-on approach to the engineering design process came from comments made by students in their end-of-course reflective essays.

“I found I learned better when I was able to put the stuff we were learning into use.”

“I improved my problem solving and decision making abilities. This course was designed to make us think outside the box and create new designs to fix a problem.”

“I’ve been told that, once a weld is completed, there will be weaker points in the metal. By creating a weld and then testing the strength, I had the opportunity to visualize what was actually happening in the process.”

“I learned a lot about the design process but, more importantly, I learned a lot about human nature.” (referring to the synergistic effect of teamwork in design)

“This course has taught me an organized method for creating something new. It has given me the building blocks to a new approach to problem solving…I think I will continue to use this approach as different projects come into my life. I can use the design process to solve any problem I am faced with.”

These examples, representative of the sentiments expressed by many outgoing ME450 students, describe an enthusiasm for engineering education that is directly linked to an understanding of the power that the design process places in the hands of human beings. The ability to design, invent, create, improve and refine provides humans with potential to influence their environment that is unparalleled in the natural world. Providing students with the basic tools of design which they can use to methodically develop their own unique solutions to complex, challenging problems has the effect of imparting intellectual excitement and inspiring an interest in engineering thought in even the most non-technical of students.

Conclusions

Course-end student feedback has indicated that ME450 was successful in meeting the United States Military Academy’s Engineering and Technology goals. More significantly, the structure and content of the course was an effective means of instilling an appreciation of and eliciting excitement for engineering science among students who had previously been apathetic or ignorant of, or intimidated by the discipline’s technical connotations. Most students left the course with a sense that they had not only successfully negotiated an academically rigorous challenge, they had been equipped with skills and abilities that they had previously not had. They were better problem solvers! To the response of what was probably the most important course assessment question, “Has ME450 improved your ability to systematically solve problems?” the answer was overwhelmingly “Yes!” The goal of providing students with a means of dreaming their dreams into reality had been realized.

The methodology used to teach the course was effective. It is likely that the valuable learning that took place would not have occurred if the course did not first break down pre-conceived barriers to learning. Excitement in the classroom, challenging assignments, and constant,
continuous feedback were the keys to encouraging reluctant students to let down their guard and experience the exhilaration of an engineering education. The exposure of non-engineering majors to the fundamentals of engineering disciplines is critical to the profession of engineering for, as Kevin J. Myers states, “…because today’s nontechnical college students are not taught about engineering by engineers, …[their] views of engineering and technology are formed by courses in history, philosophy, and related fields. As engineering educators we have both the obligation and opportunity to change this situation.…”

USMA’s ME450 provides an innovative template to accomplish this objective.

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References

3. Lowman, Joseph, Mastering the Techniques of Teaching, second edition, Wiley, San Francisco, 1995, pp. 195-196. Bloom’s Taxonomy describes a hierarchy of six levels of cognitive learning, beginning with the ability to recall and recognize information, then incorporating the progressively more complex abilities to comprehend, apply, analyze, synthesize and, finally, critically evaluate knowledge.
4. Lowman, pp. 5-10.
5. 76 percent of students enrolled in ME450 during fall semester, 2006, responded with “always” and 20 percent responded with “frequently” to the statement, “My instructor used well articulated learning objectives to guide my learning.” 90 percent of enrolled students responded with “always” and 6 percent responded with “frequently” to the statement, “My instructor had a structure or plan for every lesson’s learning activities.”
8. 76 percent of students enrolled in ME450 during fall semester, 2006, responded with “always” and 21 percent responded with “frequently” to the statement, “My instructor cared about my learning in this course.”
10. 88 percent of students enrolled in ME450 during fall semester, 2006, responded with “always” or “frequently” to the question, “Did this course improve your ability to systematically solve problems?”