AC 2008-2193: ENGAGING FIRST YEAR STUDENTS IN ENGINEERING DESIGN THROUGH ENGINEERS WITHOUT BORDERS

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Engaging First Year Students in Engineering Design through Engineers Without Borders Projects

Abstract

It is important that first year engineering students learn that the engineering design process involves more than mathematics and physics. To accomplish this, students choose design projects from a variety of disciplines, developed with *Engineers Without Borders (Canada)* and situated in either a developing country or a remote area of Canada. All projects required, not only a technical solution, but also consideration of ethics, health and safety, economics, and impact on the community. Among the design projects were a rain-water harvesting system and ceramic water filter for villagers in Cambodia and a press for extracting oil and producing biodiesel fuel from seeds of the Jatropha shrub, which grows in West Africa. The impact of this approach on student satisfaction and success is discussed.

Introduction

A central focus of engineering education is the design process. Our goal as engineering educators is to ensure that graduating engineers have the ability to "design effective solutions that meet societal needs" [1]. Traditionally, engineering education is built on a foundation of sciences and mathematics courses, with students taking engineering courses in their upper years, with few students experiencing design outside of a focused course in their discipline. In the 1990's, in response to accreditation criteria, most engineering schools added a "capstone" design project in the final year. These projects are meant to be complex, have a "real world" flavor, and are often multi-disciplinary. In some cases, there are industrial sponsors and students work closely with practicing engineers.

As engineering education has evolved in the last decade, the concept of a "cornerstone" or first-year engineering design project has been added. The goal of these projects is to give students early exposure to the engineering profession[2-4], the engineering design process[5], and the diversity of engineering disciplines; all while keeping their excitement, enthusiasm, and enjoyment levels high.

Teaching first-year students about the engineering approach to problem-solving and design provides them with a framework within which to apply core scientific knowledge and mathematical skills they are acquiring in other courses. As part of our *Introduction to Professional Engineering* course, small groups of students work together on design projects. Students choose from a set of topics that reflect the diverse engineering disciplines within our faculty. The project descriptions were developed in collaboration with *Engineers Without Borders (Canada)* and are set in either a developing country or a remote area of Canada. In addition to the technical aspects of the engineering design, the final reports and presentations address considerations such as ethics, healthy and safety, economics, and impact on the community. Design projects included, for example, a rain-water harvesting system, a ceramic water filter, a seed press to extract oil, and a process for converting seed oil into biodiesel fuel in communities such as Lehkbooan, Cambodia and Changnayili, Ghana.

Course Model

The *Introduction to Professional Engineering* course is taught over two terms (25 lecture weeks), with the first term focused on teaching the appropriate background to enable students to complete two design projects in the second term. The class of 850 students is divided into four sections for weekly lectures.

The course teaches professionalism, problem-solving, and engineering design. The first topic included professional ethics, responsibilities, licensing, and legal aspects, such as contracts, liability, and intellectual property. In the 2005/06 and 2006/07 academic years, students were taught using a mix of traditional lectures presented by the instructor as well as "case study" lectures given by experts from various fields of engineering. These lectures were based on real-life engineering problems and contained a balance of abstract concepts and concrete details illustrating how the design process works and how problems are solved in practical engineering situations. Case studies often included a compelling dramatic story to engage the students, such as the structural failure of the World Trade Center, material failures in two Space Shuttle disasters, and the transformation of Penicillin from the initial scientific discovery to engineering production on an industrial scale. In 2007/2008 we have moved from this model to focus on teaching fundamentals of the profession, professionalism, and ethics as it applies to everyday practice. Although some of the old material was retained, particularly with respect to the ethics of catastrophic failures and the engineer's responsibility to prevent harm and loss of life, the new curriculum includes highly practical material and helps the students delve into more common ethical questions. A new textbook by Gunn and Vesilind[6] was adopted as well as a new lecture methodology. Rather than approaching this material using traditional passive lecturing, a discussion-based approach has been adopted. Early response from the students has been highly positive.

Table 1. Comparison of course assessments.

	2005-06, 2006-2007 Academic Years		**2007-2008 Academic Year**	
	Number of Assignments	Weighting (%)	Number of Assignments	Weighting (%)
Technical Writing Essays	2	20	2	20
Excel Spreadsheet	1	10	-	-
Readiness Assessment Test (in-class quizzes)	15	10	12	10
Design Projects	2	40	1	20
Tutorial participation	-	-	-	5
Mid-term examination	1	20	1	35/20*
Final examination	-	-	1	20/35*

* Note: The weightings on the mid-term and final exams will be either 20 or 35%, whichever will benefit the student in terms of their final grade.

In the 2005/06 and 2006/07 academic years, students in the course were evaluated based on five components (as summarized in Table 1): two technical writing articles (20%), one computer assignment (10%), one midterm examination (20%), 15 in-lecture Readiness Assessments Tests[7,8] (10%), and two design projects (40%). This year, the students will be evaluated based on two written assignments (10%), a midterm, in-lecture quizzes (10%), and the design project including interim work, presentation, and final report (20%). After evaluating the attendance data for the last two years, a final exam in Term 2 has been added this year. The weightings for the mid-term and final exams will be 20% for one and 35%, assigned to maximize the student's final grade.

In past years, students were given formal lectures on technical writing and oral communication skills, and asked to write two 1000-word technical articles inspired by case study lectures, but including additional research that explored some particular aspect of the topic in greater detail. Students were expected to express their own opinion on an engineering issue, present facts and evidence, and draw a conclusion. An important part of the learning process was the "peer evaluation", in which students graded each other's work and calibrated their own performance. A few students chose not to write one or both articles. In some cases plagiarism was an issue, either because students were ill-prepared to write a technical article in English, they did not understand issues of academic integrity and ownership of intellectual capital, or simply because they did not allow themselves the time to complete the assignment and thus, resorted to copying at the last minute. Because performance on the articles was not significantly correlated with success in the course (final grade) and because we found that first-year engineering students did not have the writing skills that allowed them to effectively write two 1000-word essays, we replaced these two assignments with two shorter pieces of writing and a number of in-lecture workshops to emphasize quality writing. In the first of the assignments, the students were asked to write a piece of professional correspondence, usually in the form of an e-mail to a professor. In accomplishing this task, the students are exposed or culturally sensitized to the community values present in both the academic community and the community of professional practitioners they will join upon graduation. The work is evaluated on its tone, punctuation, spelling, grammar, capitalization, succinctness, brevity, and persuasiveness. Students were prepared for this assignment in lecture through the use of case studies of previous students' communiqués and peer evaluated in-class exercises. In the second assignment, students discussed their solution to an ethical issue. The students were prepared in a similar way for the second assignment using in-lecture exercises and case studies.

Computational problem-solving skills were developed and evaluated using two computer assignments in which students (working in pairs) analyzed empirical data, fit theoretical equations, graphed results, and formulated conclusions. This exercise was eliminated this year because it no longer was needed to meet any of the learning objectives of the course. Formerly, some of the design projects depended on the student's ability to use a computer-based spreadsheet. Since the design projects have been significantly modified, they no longer have this requirement.

A major challenge in many engineering courses is engaging students and motivating them to come to class regularly. It is difficult to teach students if they are not there. For about sixty percent of the lectures, Readiness Assessment Tests[7,8] (RAT) were used to ensure students completed an assigned reading and attended class. Most of the in-class quizzes had three multiple-choice questions. Some students developed creative strategies to avoid doing readings or attending lectures, such as bringing a laptop to scan the reading for answers, getting the quiz from one class, hoping questions in another class might be similar, or showing up in the last five minutes of class hoping to get the answers from a friend and complete a quiz. Others simply completed the quiz and left. Despite the fact that each quiz was worth very little, attendance was remarkably high (about 80 – 95% throughout the first term of the course). However, in Term 2, as shown in Figures 1 and 2, attendance dropped considerably. Correspondently, the RAT scores also decreased significantly in Term 2 as compared to that observed in Term 1 (as shown in Figure 3).

A weak correlation ($r = 0.348$) was found between student performance on the first term quizzes and the midterm December examination. The quizzes were originally designed to encourage attendance at lecture and as an incentive to prepare for the lecture by reading the material prepared by the instructor. It was thought that a prepared student would be more engaged in the material presented in the lecture and therefore the learning outcomes of the course, as measured on the midterm exam, would be met. The cause of the weak correlation is unclear. However, several factors may have contributed. Firstly, in the large lecture section (200 to 250 students) the lecture quizzes were distributed by allowing students to pick-up the quizzes and then return the quizzes on their own without direct contact with the instructor. This was done in a haphazard fashion, allowing the students ample opportunity to cheat by collecting multiple quizzes, completing them all on behalf of absent peers, and then submitting them without the instructor's notice. Since some students looked up the answers during the lecture, they may not have truly assimilated the material, and therefore, did poorly on the December exam. Finally, as the quizzes were not generally challenging to the students, they may not have taken the material seriously. Consequently, the grades were distributed with a low standard deviation and this may have lead to the poor correlation.

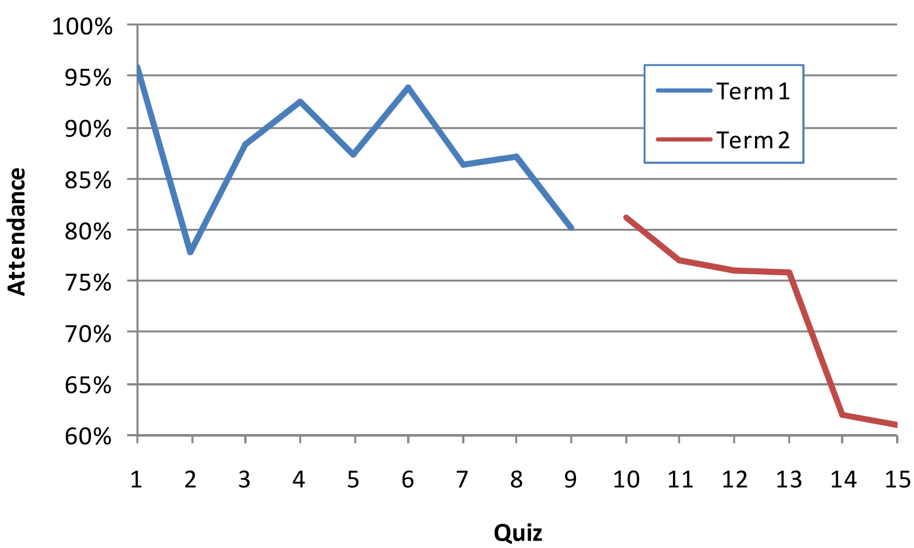

Figure 1. Attendance at lectures (as measured by the number of quizzes completed) for the 2006 – 2007 academic year.

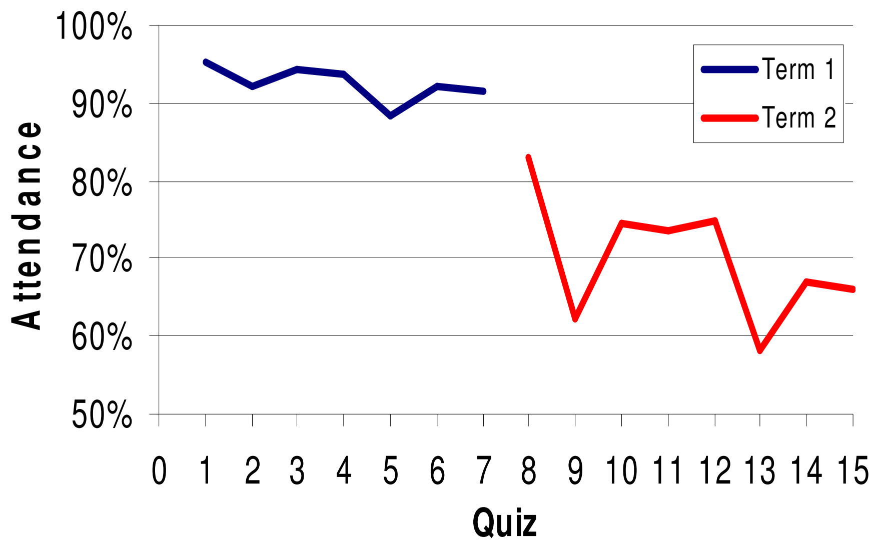

Figure 2. Attendance at lectures (as measured by the number of quizzes completed) for the 2005 – 2006 academic year.

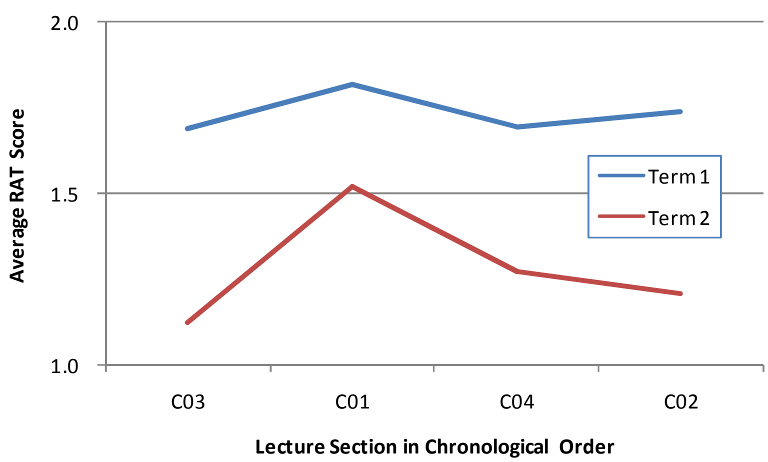

Figure 3. Correlation between RAT scores in Term 1 and Term 2 with section for the academic year 2006 – 2007.

It was also noted that there was essentially no correlation ($r^2 = 0.0176$) between the first writing assignment and the mid-term exam in 2005-2006. This is not surprising since the writing assignment required the investigation of a single topic of interest to the student. The December exam was multiple choice and the questions were fairly trivial in nature. It should also be noted that the writing assignment grades were all skewed upwards. This was the result of a marking scheme where the minimum a student could earn was a 65% if they completed an assignment.

Design Projects

A challenge in formulating the design projects is that first-year students lack technical sophistication. With this in mind, the first set of seven design projects was developed in conjunction with *Engineers Without Borders (Canada).* These projects involved relatively low-tech engineering solutions that would benefit disadvantaged communities in developing countries. The remote setting also emphasized the importance of understanding the conceptual side of design. Students were required to understand the client needs, opportunities, and benefits and make realistic conclusions about the cost, feasibility, and impact on the community.

In previous years, during the second term, students were expected to complete an engineering design project during an intense six-week period, and then repeat the process a second time for a different project. Students were assigned to some 200 teams (3 – 5 students each) and divided into 16 tutorials, supervised by 87 teaching assistants (12 graduate, 75 undergraduate) and 7 faculty consultants. Students were guided in structured tutorials, group discussions, and computer-mediated interactions. To ensure students made steady progress, there were three deliverables: a preliminary report describing background research, ethical considerations, and design alternatives; a final report that included the team's proposed technical design, cost analysis, feasibility, and impact on the community; and an oral presentation before an audience of 50 students (first project) or an interactive poster presentation (second project). Grading reports and presentations included "peer evaluation" as an integral part of the learning process.

Three teams with the best presentations were selected and given additional coaching and instruction before giving oral presentations to the entire class in a special evening event, with additional presentations from *Engineers Without Borders (Canada)*. Recognition was given to other student teams with awards for best technical reports, most innovative designs, and most impressive humanitarian ideas.

To ensure that students also learned about modern engineering with direct relevance to careers in North America, the second set of projects were developed in consultation with seven engineering departments and situated in remote Canadian communities. Example topics included: ethanol production, footbridge design, alternative fuel engine, wind turbine, and text-writing robot.

Critical Assessment

When assessing the product of past design projects in the course, invariably the evaluators were disappointed, with the occasional exception of a surprising design such as a design group that concluded after careful research and deliberation that it was not possible to design a solar panel for recharging car batteries in a way the met the constraints of the client and user from the underdeveloped world. More often than not, faculty comments suggested that the projects lacked "depth" and any form of creativity or innovation. These common observations have been attributed to poorly formulated projects, insufficient guidance on the projects, and a lack of teaching assistant training.

Until the 2007/8 academic year, the projects were either developed in collaboration with *Engineers Without Borders (Canada)* or solicited from the engineering departments at the Faculty of Engineering. These "departmental" projects were drawn from the disciplines chemical, civil, computer, materials, electrical, engineering physics, mechanical, and software. Both the variety and type of project deemed appropriate by the contributed by the departments suggested that faculty themselves do not have a consistent notion of what engineering design is or should be. Hazelrigg[9] suggests that design is essentially the process of the searching to the find the design concepts and parameters that best meet the needs and wants of the clients and users. Generally the product means a physical or informational artifact that includes products such as automotives, cell phones, software. The key is that engineering design involves both divergent and convergent thinking[10]. Divergent thinking, the creative aspect of design, is the process of generating ideas and concepts. Convergent thinking is normally linked with the systematic evaluation of alternatives and rational decision making required to select from amongst a set of design alternatives. In the engineering design process, the incorrect assumption is often made that the mapping from what the clients and users want and need to engineering specifications is both straightforward and trivial. In this light, a number of the projects used in the past were found to be inadequate.

For example, one of the department projects involved the calculation of parameters to determine the size of a beam needed in the truss structure of a bridge based on a strength criterion alone. Although this is clearly a step in the design process, this project offered no opportunity for selecting between designs or design concepts. It is indicative of the convergent thinking that predominates undergraduate engineering courses. Often the projects were found to be flawed in so much as they required students to design using technologies that were beyond their comprehension as first year students. Asking students to design a “writing robot”, while potentially a very challenging and interesting task, led to situations where students were unable to generate ideas or alternatives, let alone be able to evaluate the goodness of a given design. It was learned that the criteria for projects that would lead to a successful design by first year engineering course required careful consideration. It may be argued that first year students are not capable of engineering design but this suggests that engineering is a technology profession that only deals with complex, highly technical solutions and has no responsibility or role in bridging non-technical users and clients with technology that can help fulfilled their needs.

Work in Progress

This year, much more focus is being placed on helping students understand the design process. Students were given traditional and case study lectures elaborating a six-step engineering design process: (1) identify problem, establish goals, (2) gather information, background research, (3) synthesis, brainstorming, classify ideas, (4) analysis, critical evaluation, (5) design selection, refinement, optimization, (6) implementation, testing, communication.

The textbook by Dim and Little[11] was adopted for the course. It is the key to providing the structure students need while learning the design process without inhibiting opportunities for creativity. In particular, the basic approach requires a number of phases. Students are asked to learn about the needs of the users and clients and organize and prioritize this information. It is emphasized that the objectives that result from this step must involve a degree of abstraction to avoid making key design decisions early in the process and thus unnecessarily limiting the design space. Furthermore, this stage represented the objectives in a language the users and clients understand. Technical terms are avoided. In the next step, students generate a set of functions, written in engineering terms, required to fulfill each of the objectives. For each function, a set of design concepts is generated. In the final phase, student teams select the combination of the design concepts that fulfill all the required functions and meet the original objectives. All work is performed in groups in a design studio environment.

While we were aware that one cannot develop the optimal solution to a complex problem without asking appropriate questions, it became clear that students did not know how to begin to generate questions and therefore could not truly identify the problem or establish goals. Tutorials to teach students how to accomplish this were developed this past summer, tested with a small group of high-achieving high school graduates, and are being used in the course this term. Although creativity is clearly required for the development of innovative solutions, the concept of creativity was not discussed in previous years. As a result, most of the designs submitted looked much the same. This year, tools such as brainstorming are being used to help students generate creative ideas.

Problem solving, while not a simple process, is essential for the completion of complex engineering problems. As noted by Dym and Little[11], students can learn to adapt to different problem situations if they understand how to focus on the individual steps in a process and how these steps interact and function together. Tutorials have been developed which allow students to solve a problem and use feedback loops to ensure that the final solution satisfies the original problem statement.

While in the past, one tutorial was dedicated to help students develop teambuilding skills and write team contracts, this was insufficient to ensure functional teams. Additional effort is being placed on developing and supporting functional teams. As part of this teaching assistants are being taught how to support the teams more effectively and how to identify problems before they become critical.

Beginning this year, the two design projects were reduced to one, to allow for greater concentration of effort on one project. The current plan calls for continuation of the design projects sponsored by *Engineers Without Borders (Canada)* but with an increased number of projects. In cooperation with *Engineers Without Borders (Canada)*, a greater number and breadth of topics were developed. Effective projects must allow for creative solutions that allow for the generation and selection of design concepts over a number of dimensions so as to the challenge the students to make complex decisions about the value of various possibilities.

The effectiveness of the course is dependent on the successful training of teaching assistants, ensuring that they understand the design skills, how to give accurate feedback on performance, and how to teach the subject matter. Tutorials for the teaching assistants were developed.

The aim of the design projects is to familiarize students with the design process and to begin to develop the mental, intellectual, and social skills required in the contemporary practices of engineering design. Selecting projects in collaboration with *Engineers Without Borders (Canada)* required careful examination of each potential project. Students are given a design statement, which is usually a single sentence that represents an idea of a device or design intended to fix a problem or improve upon an existing design. Furthermore, students are given a profile of the users' culture, location, living conditions, and economic situation. It is emphasized that the students are designing for one clearly defined user who is an individual, a family, or small community. The designs are not intended to be commercialized. It was found that students often construe product as meaning a mass-product commercial venture and loose sight of the idea that a product is intended to improve the quality of life of the its users. Projects must have a specific device or design ideas embedded within the design statement that is plausible. Broad statements that suggested a problem but not device or technology that may help to solve are deemed inappropriate for the nature of the course.

The central objective of the design project with respect to previous years is to have the students create a unique design. Often in the past the lack of depth involved in learning about the problem led to plethora of very similar and mediocre design efforts. To improve on this lack of uniqueness, design statements were selected that fulfilled two primary objectives. Firstly, they allowed for richness in the exploration of user and client needs. For example, one design statement asked students to consider the design of a ventilation device for a traditional stove in a village in Ghana. For successful projects, students need to ask questions regarding the purpose of the device: for example, whether it was intended to remove heat from the home, remove odors, or eliminate the noxious smoke particles. Once a better understanding of the problem was involved, students could move onto asking questions regarding the type of stove, its use and users, safety considerations, construction of the home, possible locations, etc. In all cases, the students are required to communicate with an *Engineers Without Borders (Canada)* representative who had spent weeks with the users and could therefore act as their representatives. To further encourage diversity in the projects, similar design statements were matched with different locations with expectations that different design would result. The second criteria for problem statement selection was the requirement that the expected design space would have sufficient number of dimensions that would require students to select from a number of possible design concepts for each of a number of different functions of the design and use multiple-criteria to determine the best design.

It was observed that students tended to approach design problems from a purely technological approach. For example, some students were presented with the problem illustrated by the photograph in Figure 4. This is a photograph of a man retrieving water from a river in Kazungula District, Zambia. The design statement asked students to design a device for safely retrieving water to avoid the ever-present danger of crocodiles to human beings. A typical response from students was to suggest designing and building a pipe to be installed in the river, which would lead to a pump on the river bank. While this concept is a plausible solution, this kind of immediate jump to a final design solution has two severe drawbacks. Firstly, since there has been no attempt to explore and understand the needs of the users, it is quite possible and most likely that the initial proposed solution, while able to fulfill its primary function, that of safely retrieving water, will fail on a number of possible fronts, which may include theft of a pump, cost, inappropriate sizing, inappropriate technology, flooding, etc. Secondly, reducing the design space to one solution may lead the design team to miss a better solution to the problem. Interestingly, it was observed that senior undergraduate students, graduate students, and even engineering faculty frequently exhibit the same biases, namely that of equating goodness of a design with only the performance of the primary function of the artifact as understood in engineering terms without reference to customer or user needs. To help mitigate this bias, a structured approach to teaching and applying the design process has been adopted in lectures and tutorials to require students to consider subjective needs separately from the technical specifications and design concepts intended to fulfill the needs. Ostensibly, this will lead and more creative solutions.


Figure 4. Man retrieving water from a river.

Conclusions

The 2007/8 course is underway with the changes to content, in particular, the delivery and learning experience with respect to engineering design. The course has moved towards engaging student interest in projects set in developing countries at a level of technology that does not require a high level of technical skill and knowledge. Setting the problems in unfamiliar countries with distinctive cultures broadens students' awareness of diversity, their understanding of professionalism and ethics.

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