

AC 2007-1866: EXPLICIT DEVELOPMENT OF ENGINEERING SKILLS AND CHARACTERISTICS IN THE FRESHMAN YEAR

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Explicit Development of Engineering Skills and Characteristics in the Freshman Year

Abstract

This paper describes a new freshman two-course sequence designed to introduce students to engineering and to explicitly develop the cognitive skills and personal characteristics of an experienced engineer. The courses focus on engineering skills associated with design and communication and on personal characteristics associated with good teamwork and effective leadership. Small group discussion related to course readings are used to increase student understanding of abstract engineering concepts. Design projects are used to facilitate student transfer of their understanding to new contexts.

The course sequence has been piloted in the Mechanical Engineering program and was shown to be quite successful with regard to student achievement and student satisfaction. Plans are being made for college-wide implementation of a similar freshman experience emphasizing skill and personal characteristic development.

1.0 Introduction

The issues of engineering student engagement and persistence and institutional retention and attrition are important from a societal standpoint^{1,2} and are addressed in many current engineering education publications^{3,4,5,6}. An initiative to address these issues (the College Core Curriculum Task Force) was established in 2003 at Marquette University. This initiative was directed toward the design of a new college-wide core curriculum focused on the “transformation” of student learning. This paper describes one of the primary outcomes from this initiative – the design and implementation of a new freshman year experience.

Early in the design process, students, alumni, faculty, and administrators were interviewed to determine the institution-specific meaning of the term “transformational” when referring to an engineering curriculum. The summary of the interview results is listed below.

The engineering curriculum will provide:

- opportunities for professional and personal interaction with caring faculty
- opportunities to interact with professionals in their field
- opportunities for independent learning
- opportunities for active learning
- clear integration between math, science, engineering, and computers
- opportunities for clearly developing skills associated with design, communication, and teamwork
- opportunities for clearly developing the personal characteristics associated with good teamwork and effective leadership
- opportunities for effective evaluation of individual student progress

The task force made specific recommendations with respect to ways in which these curricular objectives could be achieved. One recommendation was to redesign the existing freshman

“Introduction to Engineering” core courses to become more experiential in nature and to provide a greater real-world context to engineering. A set of four integrated courses was described: one primarily addressing computer modeling skills, one primarily addressing graphical communication skills, and two sequential courses primarily addressing engineering design, communication, and teamwork. The latter two courses are the subject of this paper.

One of the objectives of the redesign of the freshman course sequence was that it act as an abstract (or “roadmap”) of the engineering curriculum as well as an abstract for a general engineering career. Other design objectives, related to the program-level objectives provided above, are that the courses: 1) engage students in activities similar to those performed by practicing engineers to allow them to make informed decisions regarding persistence in engineering, 2) motivate the need for the analysis skills that are the focus of subsequent coursework; 3) motivate, define, and exercise the skills and characteristics of an experienced engineer related to design, communication, and teamwork, 4) demonstrate the importance of these not-exclusively-analysis skills and characteristics to students, and 5) instill a positive attitude toward learning and professional development.

This paper describes the design, realization, and evaluation of the courses developed to fulfill these objectives. Section 2 identifies the specific student learning objectives in each course and the educational strategies used to facilitate student learning. Section 3 briefly describes both student and instructor assessment of how well the course facilitated the student learning objectives. Section 4 provides a brief summary and conclusions.

2.0 Student Learning Objectives and Educational Strategies

This section identifies the specific learning objectives of each course in this two-course sequence and the strategies used to facilitate these learning objectives. The scope and nature of each course is reflected in their respective titles. The first course in the sequence is titled, “Engineering: The Art of Creating Change”. The title of the second is: “Engineering Projects: The Practice of the Art”.

Both courses use assigned reading followed by reflection, writing, and discussion related to a debatable question (or questions) posed by the instructor. Section size is limited to 25 students. A relatively senior member of the regular faculty and one teaching assistant facilitate class discussion using Socratic questioning.

Both courses also use design projects as vehicles in developing student understanding of key concepts. In the first, the course requirements manage student-team project activities; in the second, the student-teams primarily manage the project activities. Project scope is significantly larger in the second course. Additional details associated with the two courses are provided below.

2.1 Engineering: The Art of Creating Change

The first course generates a link between engineering and society and a link between engineering education and engineering practice. The link to society also serves as a link to the institution,

where service is a central part of the institutional mission. The course articulates how engineers can create beneficial change in society throughout their lifetime in a career of service. The early link to engineering practice is directed toward having students take ownership of their learning. The published specific learning objectives of the first 2-credit course are listed below.

Upon completion of the course, each student should be able to:

- describe the roles of engineers and their importance to society;
- describe the nature of engineering problems and strategies for their solution;
- identify and use each of the skills needed for effective engineering problem solving;
- identify and use each of the tools used to limit risk in making engineering decisions;
- identify and demonstrate characteristics important in good teamwork and leadership.

The strategies invoked to achieve each of these objectives are described below.

2.1.1 The Roles of Engineers and Their Importance to Society

Students are involved in three activities to develop their understanding of the role of engineers and their importance to society. These activities are: 1) summer reading of a book⁷ motivating the need of more and better engineering to improve the environment and the quality of life followed by reflection, writing, and discussion, 2) reading, reflection, writing, and discussion related to technology, society, and ethics, and 3) research into the different types of engineering followed by reflection, writing, and discussion related to their career interests.

2.1.2 The Nature of Engineering Problems and Strategies for Their Solution

Students are involved in two activities to develop their understanding of the nature of engineering problems and strategies for their solution. These activities are: 1) reading of selected chapters from a book⁸ that describes engineering as problem-solving with uncertainty and limited resources, followed by reflection, writing, and discussion, and 2) reading related to a good general problem solving strategy (including an academic-problem solution template) and student exercises in which four progressively more difficult problems are solved, initially by individuals and the last one by a team.

2.1.3 The Skills Needed for Effective Problem Solving

The cognitive skills needed for effective problem solving are introduced to the students on the first day of class and referenced and reinforced throughout the year. The specific cognitive skills described and developed are:

Perception – understanding problem/opportunity as presented by client/management/world

Synthesis – generating ideas/approaches to problem-solution/opportunity-satisfaction

Analysis – evaluating promising ideas/approaches

Selection/Rationale – selecting and justifying the “best” idea/approach

Realization – implementing or reducing the level of abstraction of the idea/approach

Verification – determining whether selected idea/approach is clear/satisfactory

Collaboration – working with others to achieve desired results/solution

Communication – transmitting results/solution to client/management/market

Each engineering skill is developed through a sequence of reading, reflection, writing, large-group (class) discussion, individual application, writing, small-group (team) discussion, and presentation. A minimum of two class periods are dedicated to developing student understanding of each cognitive skill. Students first read an assigned article that describes a somewhat abstract specific engineering skill. Students then reflect on the reading and prepare a response to a debatable question that requires understanding of the reading's content. In the first class period, the responses to this question (and any other questions that the students have about the reading) are discussed. Next, each student is asked to apply the skill to an assigned small-scale design project. Students meet on teams to share their perspectives on the appropriate application of the skill to their project. In the second class period, a member of each student team presents the results of the team-selected appropriate application of the concept to their project.

In addition to the reading-reflection-writing-discussion-application instructional processes described above, the "communication" skill is developed in other ways throughout the semester. Most class time is used to develop student oral communication skills in informal class discussion or in relatively formal student presentations. The written essays/reports described above that are due each class period are edited and graded with respect to content, clarity, and professionalism. In addition, there are three formal reports submitted by each team that document results of their design process – a project definition document, a concept selection document, and a design final report.

The "collaboration" skill is also developed using several additional methods to those described above. The class is informed that class discussion is a collaborative activity directed toward a clear common understanding of the concepts contained in the reading material. Student contribution to class discussion is both self-assessed and assessed by the course instructor. Collaborative skills are also self- and peer- assessed in the team project.

The project in Fall 2006 was to design and fabricate an instructional toy car to be used to demonstrate physics principles to middle-school students at a cost of less than \$20. In the discussion and application of each cognitive skill, students were not specifically told "what to do", but were told that "support for their design decisions was expected". For example, when "perception" was addressed in the first class period, the reading and discussion focused on three relatively abstract ideas: understanding the current situation (problem or opportunity), defining the project scope, and specifying desired performance (not specifically how to apply these ideas to their project). Each student was then asked to describe how he or she would apply these concepts to his or her project in the second class period. Each team then reviewed its members ideas, then selected and executed their plan for applying these ideas to their project, and finally documented their results in a "project definition" report, which was evaluated for both content and presentation.

2.1.4 The Tools Used to Limit Risk in Making Engineering Decisions

Two class periods are used to address most of the cognitive skills identified above. More class time, however, is directed toward the "analysis" skill to better frame the activities of an experienced engineer and the significant emphasis on this skill in engineering education. The

types of tools used to limit risk in making engineering decisions that are described and developed are:

- Historical Models – existing data, charts, maps
- Analytical Models – mathematical models
- Numerical Models – computer models
- Physical Models – fabricated physically similar models

This component of the course is directed toward motivating the analysis skills subsequently developed and emphasized in the engineering curriculum. The difficulty of dealing with uncertainty in making engineering decisions (described earlier in the “nature of engineering problems”) is used to provide context to discussion regarding the application of the analysis skill and the selection of appropriate models for specific practical (non-academic) problems. The tradeoff between model accuracy and limited modeling resources is made explicit

2.1.5 The Personal Characteristics Needed for Good Teamwork and Effective Leadership

Like the cognitive skills, the personal characteristics are introduced to the students in the first day of class and referenced and reinforced throughout the year. The specific personal characteristics described and developed are:

- Productivity – action and results orientation
- Responsibility – social impact and environmental impact awareness
- Integrity – fairness, justice, openness, and honesty
- Supportiveness – collaborative nature and respectfulness
- Enthusiasm – positive attitude and growth orientation

Unlike the development of the cognitive skills, little class time is dedicated toward describing these collaborative characteristics. Several course activities, however, are directed toward exercising and reinforcing these characteristics. Students assess their own preparation and contribution to class discussion using these criteria. Students also self-assess and peer-assess their activities on their team project using these same criteria.

2.2 Engineering Projects: The Practice of the Art

In the second course, each skill is further developed through their application to a larger-scale design project with less direct guidance as to the specific skill or characteristic to be invoked at a particular time. In this course, students are expected to self-manage their design project. To facilitate this, more powerful tools for project management and design communication are introduced and exercised. This is accomplished through reading, reflection, writing, discussion, and later application to their project.

The published specific learning objectives of the second 2-credit course are listed below.

Upon completion of the course, each student should be able to:

- describe the engineering design process and apply it to engineering problems;
- describe project management functions and apply them to engineering projects;
- identify the components of project status reports and write/present effective reports;
- design and fabricate simple electro-mechanical (mechatronic) systems.

- identify and demonstrate characteristics important in good teamwork and leadership;

2.2.1 Effective Engineering Design Processes

An engineering design process and tools useful in this process are provided to the students in assigned reading⁹. In that the reading constitutes a second exposure to a generic design process (students are “walked through” a design process in the first semester when the cognitive skills are defined and exercised), the material is covered at a relatively rapid pace. Most of the focus in this second exposure is directed toward developing student understanding of the importance of specific tools used to help summarize process results in tables, charts, or graphs.

To develop student understanding of effective design processes, students are engaged in reading a portion of the text, reflection on the most important and most confusing concepts, writing that identifies and justifies the selection of the important concepts and identifies the confusing concepts, and large group (class) discussion related to the important and confusing concepts.

Development of student understanding of these concepts and tools is important for facilitating positive outcomes in their design project. Quality project outcomes are also facilitated by instructor/student-team interaction scheduled into the course schedule, i.e., class time dedicated to “technical consultation”. The development of student understanding of the design process and associated communication tools allows the students to have a clear, common understanding of the processes and tools. This common understanding not only facilitates good communication within each team, it also facilitates good communication between students and instructors.

The project in Spring 2006 was to design and fabricate a scaled-down model of a Martian rover to obtain three geologic samples using a Vex robotics kit and an additional \$100 for custom parts/materials. The project culminates with the end-of-semester “grand challenge” in which each design is tested in the “field”, a mock-up of a Mars landing site. The collection of one of the geologic samples (a 4 ounce sample from a limestone $\frac{3}{4}$ – 1 inch slab) requires more power than that obtained in the standard Vex kit. This aspect motivates the development of more sophisticated analysis skills to determine the amount of force/energy required to remove a rock sample. The analysis is facilitated through interaction with the course instructors during class periods dedicated to “technical consultation”.

2.2.2 Effective Project Management Functions

Unlike the design processes, the project management functions are not explicitly developed in the first semester course. In the first semester, the course syllabus establishes the project timeline –a project related interim deliverable is due every other class period. In this second course in the sequence, project management functions of planning, organizing, leading, and controlling are described in the reading⁹ and exercised in the course. Student prior experience (in the first semester project) in conjunction with the reading motivates student understanding and application of specific tools used to help summarize process results in tables, charts, and figures.

The approach used for design processes instruction is also used for management functions instruction. To develop student understanding of effective project management functions, students are engaged in reading a portion of the text, reflection on the most important and most confusing concepts, writing that identifies and justifies the selection of the important concepts and identifies the confusing concepts, and large group (class) discussion related to the important and confusing concepts.

Although the student-teams are described as “self-managed”, aspects of project management are mandated by the course (to prevent “self-managed” from being misinterpreted as “non-managed”). Activities associated with the management functions of “planning”, “organizing”, and “controlling” are required.

A “project definition document” that includes aspects of “planning” and “organizing” (e.g., a project timeline decomposed to the task-level with responsible individuals identified) is due relatively early in the project. Additional “milestone deliverables” such as a “concept selection document”, a “performance verification report”, and a “final design report” are also dictated by the course.

Some level of “controlling” is also mandated and is described briefly in the subsection below.

2.2.3 Effective Project Status Reports

Some level of the “controlling” aspect of project management is also mandated by the course in that oral project status reports to the class are required every other week. The class audience is asked to perform the role of a “design review team” for each project team presentation. Students and instructors evaluate the content, clarity, and professionalism of each status report.

2.2.5 The Personal Characteristics Needed for Good Teamwork and Effective Leadership

The set of personal characteristics identified in Section 2.1.5 are again used as criteria to evaluate student activities directed toward exercising and reinforcing those characteristics needed for good teamwork and effective leadership. Students again assess their preparation and contribution to class discussion at the end of each discussion period using these criteria. Students also self-assess and peer-assess their activities on their team project (at mid-term and end-term) using these same criteria.

3.0 Course Sequence Quality Assessment

The individual courses have been evaluated by both the instructors and the students. This section describes the qualitative assessment of the courses from both the instructor and student perspectives and the student-reported quantitative assessment of courses with respect to several measures.

3.1 Qualitative Course Assessment

For both courses, instructor evaluation is quite high. Student performance indicates significant student engagement and significant student learning. Many students appear to be engaged in metacognition – thinking about their thinking and identifying what an appropriate cognitive skill might be at the current stage of a project. Student communication skills appear to be dramatically improved. Collaborative abilities also appear to be quite good.

Project results were also quite good. Although (or maybe because) freshmen have rather limited analytical capabilities, they seem to be relatively receptive to the idea that engineering problems do not have a single, right answer. As such, they seem to address the uncertainties and open-ended nature of engineering projects with less difficulty than that demonstrated by upperclassmen.

Students describe both courses as demanding, but many also claim that they “have learned more in this course than any other”. In course evaluations, several students commented that the courses should be “worth more than 2 credits”.

Most students very much enjoyed the open-ended nature of the design projects and now feel empowered by their experience. In course evaluations, when asked about what was best about the course, one student stated that, “I like that, as the course went on, I could see my teamwork and leadership abilities greatly improving. I also like the feeling that I understand greatly what it means to be an engineer and how I can now apply my knowledge to develop solutions to any problem.”

3.2 Student Quantitative Course Assessment

Three student self-report assessment instruments were used to evaluate student learning. Two surveys (one at the end of each course) were used to assess how well the course satisfied its student learning objectives and a design-course standardized survey was used to assess student progressive development (at the end of the second course).

A summary of the assessment of student learning in each of the two courses is provided in Table 1 and Table 2, respectively. The survey reported in Table 1 was administered in Fall 2006 to 57 students. The survey reported in Table 2 was administered in Spring 2006 to 55 students.

Table 1. Student Assessment of Achievement in Course 1 Learning Objectives

(scale: 1 = not at all; 2 = not very well; 3 = adequately well; 4 = very well; 5 = extremely well)

How well has the course developed your understanding of:	Score
the roles of engineers and their importance to society?	4.04
the nature of engineering problems and strategies for their solution?	3.90
the skills needed for effective engineering problem solving?	3.95
the various models used to limit risk in making engineering solutions?	4.05
How well has the course developed in you:	
the personal characteristics important in good teamwork and effective leadership?	3.80

Table 2. Student Assessment of Achievement in Course 2 Learning Objectives
(scale: 1 = not at all; 2 = not very well; 3 = adequately well; 4 = very well; 5 = extremely well)

How well has the course developed your understanding and ability to perform:	Score
engineering design processes?	4.15
project management functions?	3.94
project status reports?	3.95
the design of electro-mechanical systems?	3.75
How well has the course developed in you:	
the personal characteristics important in good teamwork and effective leadership?	3.85

The summary of the assessment of the second course with respect to the “Engineering Coalition of Schools for Excellence in Education and Leadership (ECSEL) Classroom Activities Survey” is provided in Table 3. The student evaluations of their development was benchmarked with respect to that for students taking the existing freshman design sequence taught using a large-lecture/laboratory format by a non-tenure-track instructor. For each of the criteria listed in Table 3, students in the new course sequence viewed their development as being significantly greater than that for the existing course sequence, with most (18 of 24) at statistically significant 95% confidence level. The survey was administered to both classes in Spring 2006 to 55 students in the new sequence and 103 in the existing freshman sequence.

4.0 Summary and Conclusions

This paper has described the two new “introduction to engineering” courses that have been developed and prototyped in Mechanical Engineering at Marquette University. The courses were designed to be motivational and developmental. Student activities are directed toward explicitly developing the cognitive skills and personal characteristics of an experienced engineer. The cognitive skills developed are associated with design and communication. The personal characteristics developed are associated with good teamwork and effective leadership.

Instructional class time in the first course is directed toward discussion about the importance of engineering and the skills and characteristics associated with being a good engineer. Instructional class time in the second course is directed toward discussion with the objective being a clear common understanding of design and management concepts. In both courses, team-oriented design projects are used as the vehicle for the skill and characteristic development.

Instructor assessment of student performance indicates significant student engagement and significant student learning. Student assessment of their development also indicates significant engagement and learning.

Plans are being made for designing and implementing additional skill and characteristic development experiences in subsequent Mechanical Engineering courses. Plans are also being made to design and implement similar freshman experiences emphasizing skill and personal characteristic development in other departments within the college of engineering.

**Table 3. Student Assessment of Course 2 with Respect to
EXCEL “Progressive Development” Criteria**
(scale: 1 = none; 2 = slight; 3 = moderate; 4 = a great extent)

Progress made, because of this course, in your:	Score
understanding of what engineers do in industry or as faculty members	3.50
understanding of engineering as a field that often involves non-technical considerations.	3.32
knowledge and understanding of the <i>language</i> of design in engineering.	3.24
knowledge and understanding of the <i>process</i> of design in engineering.	3.61
Progress made, because of this course, in your ability to:	
do design.	3.53
solve an unstructured problem.	3.57
identify the knowledge, resources, and people needed to solve an unstructured problem.	3.25
evaluate arguments and evidence so that strengths and weaknesses of competing alternative can be judged.	3.14
apply an abstract concept or idea to a real problem or situation.	3.30
divide unstructured problems into manageable components.	3.34
clearly describe a problem orally.	3.10
clearly describe a problem in writing.	3.18
develop several methods that might be used to solve an unstructured problem.	3.43
identify the tasks needed to solve an unstructured problem.	3.38
visualize what the product of a project would look like.	3.37
weigh the pros and cons of possible solutions to a problem.	3.37
figure out what changes are needed in prototypes so that the final product meets specs.	3.54
develop ways to resolve conflict and reach agreement in a group.	3.17
pay attention to the feelings of all group members.	3.15
listen to the ideas of others with an open mind.	3.38
work on collaborative projects as a member of a team.	3.63
organize information into categories, distinctions, or frameworks to aid comprehension.	3.17
ask probing questions that clarify facts, concepts, or relationships.	3.21
after evaluating the alternative generated, to develop a new alternative that combines the best qualities and avoids the disadvantages of the previous alternatives.	3.33

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