Lessons Learned from Teaching Project Based Learning Communication and Design Courses

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Introduction

Since its inception, the college of engineering at Rowan University has maintained a focus on experiential, or project based learning[1]. At the heart of the Rowan college of engineering curriculum are the Engineering Clinics, an 8 semester course sequence[2] designed to foster real-world engineering skills, many of which are now designated as the ABET A-K objectives[3,4]. In addition to these skills, the Sophomore Engineering Clinics (SEC I & II) are specifically charged with teaching design and communication.

The purpose of this paper is to present four tenets on teaching communication and design that were recently explicitly stated by the Sophomore Engineering Clinic faculty, and discuss how these have affected the way that SEC I & II are being taught at Rowan University. First, a brief description of the structure of SEC I & II is presented. Next, each tenet is listed, followed by an explanation and discussion of the observations that led to the statement of that tenet, and specific changes that were made as a result of the realization. Finally, general recommendations for teaching communication and design are made.

SEC I and II at Rowan University

Sophomore Engineering Clinic I and II are taken by all sophomore engineering students at Rowan University. A schematic diagram illustrating the content of the two-course sequence, as taught in the 2004-2005 academic tear, is shown in Figure 1. In the fall semester (SEC I), the students are split into two different lab sections, each with approximately 60 students. All students work on the same projects in SEC I. First, student teams work on a four-week rocket design project. Then, student teams work on a ten-week crane design project. These projects were described by von Lockette, *et al.*[5] and Dahm, *et al.*[6], respectively. Simultaneously, Students receive instruction in technical writing in small sections. In the spring semester (SEC II), all 120 students are in a single design lab section, but are allowed to choose between two distinct projects. The greenhouse gas reduction project was run from 2003 through 2006, and is described in detail by Riddell, *et al.*[7] The electro-mechanical project was run in 2006 and 2007, and is described in detail by von Lockette, *et al.*[8] Simultaneously, students receive instruction in public speaking in small sections. In spring 2007, the greenhouse gas project was replaced by a different project, which is not discussed in this paper. Brief descriptions of the four projects, extracted from the papers referenced above, follow.

The first design project in SEC I is the bottle rocket project. In the bottle rocket project, students use 0.25 inch thick foam board, duct tape, a 2 liter soda bottle, modeling clay and water to design rockets that can be launched from a nozzle by using pressurized air. This concept has been used at other universities to teach core engineering principles[9], and NASA has proposed standards and lesson plans to use for grade 5-12 students[10]. Student teams design rockets in the first lab period, charged with designing a rocket that can fly as far as possible. For the first week, the teams are limited only by the materials, configuration of the launch pad, and set air pressure. This first class had been utilized as an ice breaker class exercise for a number of years in SEC I.

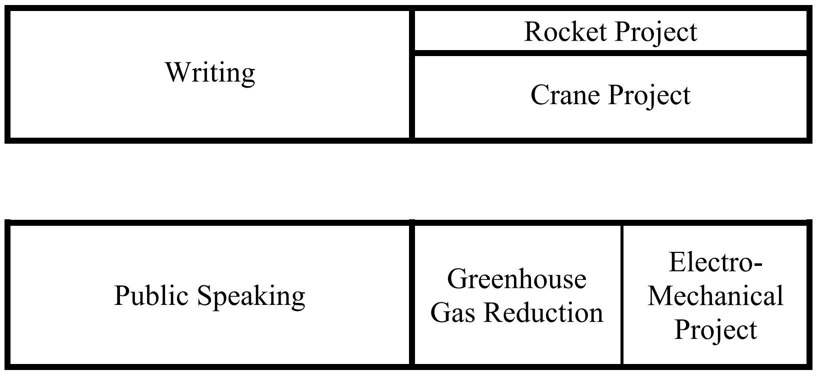

Figure 1. Schematic figure of topics for Sophomore Clinic sequence. In SEC I, all students complete the same sequence of projects. In SEC II, half of the class participates in a greenhouse gas reduction project, while the other half executes an electromechanical design project.

In the fall of 2005, the bottle rocket project was expanded to a four week project. The first lab period of the expanded project is essentially unchanged from the original version one-week project. In the second lab period, students are given a new, but highly constrained design challenge, and have three weeks to develop their designs. Student teams are asked to choose a single family of wings (their choice) that is characterized by a single parameter—for example, triangular wings with fixed aspect ratio and angles, but variable size. The teams are limited to using exactly three wings belonging to the chosen family, mounted 120^o apart, and placing the modeling clay in a mass at the front of the bottle. A schematic figure of a rocket is shown in Figure 2. By varying the single parameter to describe the wing, the mass of clay, and the mass of water put in the rocket, students have a three-dimensional design space to solve a parametric design problem. Students use experimental data from tests, informed by trends from analytical models (the so-called rocket equation to predict the impulse given to the rocket, particle dynamics to model flight path, etc.) to converge on their optimized design.

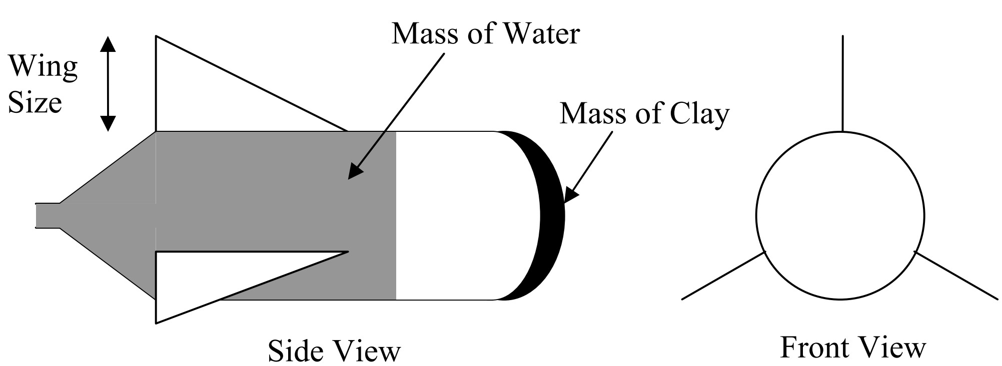

Figure 2. Schematic figure of bottle rocket with three design parameters identified. "Wing size" may be the height of the wing, its aspect ratio, or any other parameter.

The second project in SEC I is the crane or "hoistinator" project. The original version of the project was described by Constans, *et al*[11]. The current version, first run in fall 2005, was described by Dahm, *et al.*[6]. Student teams have ten weeks to design and construct a truss made of aluminum and plastic bars that the students attach to an existing I-beam. A three-horsepower motor, a cable, and a series of pulleys are used to lift weights. A schematic figure of a truss, frame, weights and motor is shown in Figure 3. Student teams are allowed three chances to lift weights, ranging from 280 to 1400 pounds. The greatest weight that is successfully lifted is counted as the strength of the crane. The students' crane designs are graded based on an explicit performance equation that is varied slightly each year but is largely driven by strength to cost ratio.

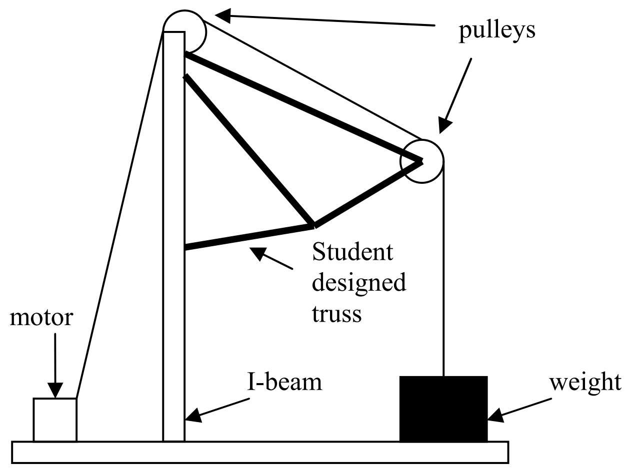

Figure 3. Schematic figure of a crane. The motor, I-beam and weights are provided; students design and build the truss structure.

The projects for SEC II are designed to be more complex than those in SEC I. The project definition is more abstract, and explicit objective functions are not given. While some constraints are stated explicitly, most are implicit, and must be identified by the students. Compared to the projects in SEC I, these projects require more advanced design skills, and more communication by team members to properly frame their design project.

One of the projects that has been run for SEC II recently is the greenhouse gas reduction project[7]. As run in the spring of 2005 and 2006, student teams are assigned to investigate one of three aspects of a specific building on campus: the heating, ventilation and air-conditioning system (HVAC); the electrical system; or the potential for a roof-mounted photovoltaic system. The objective of each team is to design cost-effective improvements to the building systems or operation that reduce the amount of greenhouse gases that are released as a result of operation of their building. In spring 2004, student teams were charged with investigating all three aspects of their building. The scope of this project was reduced to make a more reasonable workload for the students.

A second project that has been run for SEC II recently is the electromechanical, or overhead crane project[8]. In teams of six, students were tasked with designing and constructing motorized vehicles capable of traversing an aboveground electrified rail system while utilizing a winch and electromagnet to lift and move objects of varying mass. Renderings of the various components are given in Figure 4. Each team was divided into three task groups consisting of two members each: vehicle design, interface design, and electronics.

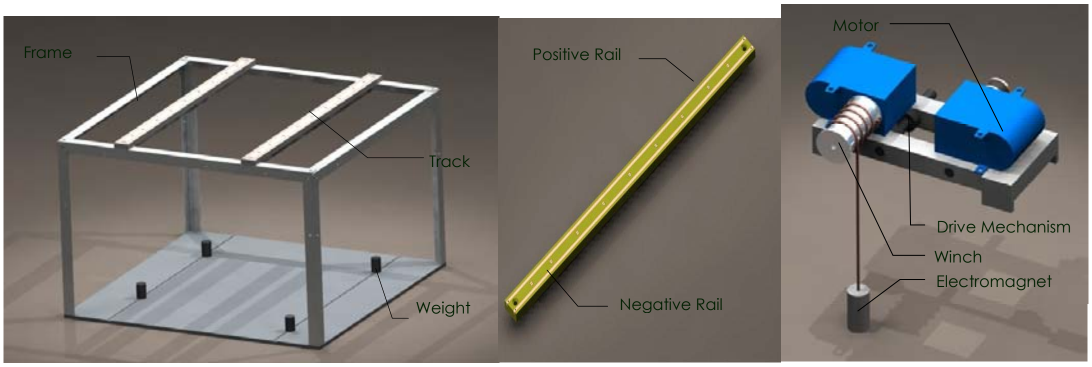

**Figure 4. Prototype systems for electromechanical project in Spring 2006.
(a) frame for vehicle, (b) powered rails, (c) prototype vehicle.**

Four Tenets for Teaching Design

The Rowan faculty recently explicitly stated a number of tenets for teaching design and communication in a project based setting. Four of these are discussed below. Student course evaluations, informal discussion with students, formal class discussions, objective and anecdotal assessment of student designs, and the literature on communication and design have informed these observations.

Building is not the same as designing.

An obvious first step in developing an experiential design course is to guide students toward developing an artifact of some type. The hoistinator was first run in 2003. In many regards, this is an excellent design project. The project affords students experience in the machine shop, complements many sophomore year courses such as statics, results in a real artifact (not just a paper design) and makes for an exciting final exam, *i.e.*, lift day; all of these factors reflect important benefits of "hands on" courses. In the first few years that the projects were run, student teams were successful in the sense that they were able to analyze and construct cranes. In all cases, cranes were able to meet the minimum requirements. In most cases, cranes were able to lift the maximum weight required. A casual observation of the artifacts, and testing of the artifacts suggested that the project was a great success.

However, at the sophomore clinic retreat in the summer of 2005, the faculty reflected on the strengths and weaknesses of the course, as taught in the fall of 2004. This reflection suggested that students were not grasping design concepts to the extent that the faculty expected. When developing the project, the faculty envisioned student teams generating a number of alternative designs, optimizing and refining the competing design ideas, identifying the best solution, and further refining toward a final, optimal solution. Instead, student teams tended to pick a nearly-completed truss design, and then use their analytical and machining capabilities to develop a solution that merely sufficed. Essentially, teams were engaged in building and testing their cranes, but were not engaged in designing toward an optimal performance score -- even though an equation for performance was stated explicitly in the design problem.

A review of the design reports reflected this approach: few teams even mentioned calculated performance scores in progress reports that identified final designs. Analytical methods were used to size members after designs were developed, but not necessarily to inform significant design choices. Comments made by students further supported this observation. For example, one student explained to a faculty member that their crane could lift nearly four times the maximum weight allowed, and then proceeded to ask if he should add more support.

Our assessment of student design work suggested that students do not inherently have effective design skills, and that merely working on design projects is not sufficient to develop undergraduates with good design skills. This observation led to a serious reconsideration in how design should be taught, resulting in a more sophisticated way to think about design education.

Students can be both creative and analytical. However, they have a hard time harnessing these skills at appropriate times during the design process.

A recent review article by Dym, *et al.*,[12] on design education presents the concept of two distinct types of thinking, convergent and divergent. Convergent thinking is concerned with answerable questions, while divergent thinking is generating new concepts or ideas. Both kinds of thinking are essential to design. When given specific prompting, students are effective at both types of thought. For example, students exhibit strong divergent thinking capabilities when they develop numerous alternative ideas for propelling rockets in a brainstorming session that concludes the bottle rocket project. Success in problem sets, exam questions and the Fundamentals of Engineering exam all point to the student's capabilities in convergent thinking.

However, when given open ended design problems, which require both convergent and divergent thinking, students have a hard time utilizing these two types of thought appropriately. Perhaps the most acute evidence of this difficulty can be found in the timing of, and the rationale behind various design decisions. In early versions of the hoistinator project, many teams made major design choices arbitrarily, and then used their analytical capabilities to size members to ensure their artifact would suffice. In some cases, final truss designs were chosen prior to any analyses being performed. Here, students were not utilizing convergent thinking when it was needed to make rational design decisions. In other cases, a final design was developed and analyzed prior to the other alternatives being suggested. In these situations, it is clear that only one idea was ever really considered, with the alternate ideas put forward merely to satisfy an explicitly stated project requirement that three designs be considered. Here, students are neglecting divergent thinking when it is needed to broaden the design space under consideration.

When explicitly asked, all student teams are capable of generating many different potential truss designs. Likewise, all student teams are capable of predicting performance scores as the result of appropriate statics and strength of materials calculations. However, as the hoistinator was taught in fall 2004, most student teams were unable to apply convergent and divergent thinking at appropriate times throughout the design process.

Schön discusses how effective designers have learned things about design that they are not even aware they have learned[13]. The authors submit that understanding when to use convergent thinking and when to use divergent thinking is one of these "things" that good designers have learned to do through practice. For most of the faculty teaching design, this learning was largely unconscious and implicit. Since there is no direct recollection of learning design (as opposed to learning a subject such as Calculus) there is a tendency to consider designing an inherent ability that can be developed (or exposed) merely through working on design problems. While it is possible to learn effective design practice in an implicit manner, it is likely that this will take years. As a result, open ended design projects are much more difficult for students to handle than the faculty initially realized.

Faced with these observations, the faculty adopted a new model for design instruction. First, the bottle rocket project was expanded from a one-class ice breaker exercise into a four-week project that emphasizes optimization through parametric design. This allows the students to concentrate, and master, a single aspect of design before attempting the more complex hoistinator project. The design projects in SEC II are, in turn, more complex than the hoistinator. The result is a three project sequence of projects that increase in both duration and complexity. The second change was to explicitly discuss the concepts of divergent and convergent thinking with the students, and require them to document evidence of both. By understanding the different types of thinking that goes on in the design process, students are better able to navigate the complex thinking that is needed for design.

Language should play a role in design education beyond representing final designs.

There are some similarities between design and communication that suggest they are natural partners in the curriculum. They are two of the most difficult aspects of the engineering profession for students (indeed, practitioners) to master. Both are inherently open ended, and require an iterative approach where ideas are generated, then refined, eventually approaching a finished product (in other words, a sequence of divergent and convergent thought processes). Furthermore, the real-world need to use language to represent final designs through written and oral reports[14] presents a strong reason to partner the subjects. However, beyond the representational purpose of language (writing *about designs*), there are additional reasons to teach communication and design in an integrated manner. Language can also serve an epistemic purpose (writing *about designing*) which is central to the write to learn movement[15]. Dong[16] argues that language it is essential to the framing of the design problem itself, and therefore language *does design*, as the language used in the design process actually affects the final product.

All three of these roles are integrated into the Sophomore Clinic Sequence. Language is used to represent designs. Students write reports about their designs in SEC I, and write reports and give presentations about their designs in SEC II. In SEC I, writing also serves an epistemic purpose. In design reports, students discuss what aspects of their design processes demonstrate convergent and divergent thinking in their reports, as well as representing their designs. In SEC II, language is an essential aspect of the design process. In the overhead crane project, the various groups within each team must communicate to allow their parts to operate in unison. In the greenhouse gas project, teams must communicate with the building's occupants and operators to gain an understanding for how the building operates, and to develop ideas about where to look for potential improvements. Throughout the two course sequence, communication and design are closely linked.

Design can be taught.

The faculty at Rowan have adopted a model for teaching communication and design in an integrated manner. Students are presented with the concepts and vocabulary to understand their designing, and then asked to discuss their designing in written reports. In this sense, writing informs design instruction as much as design informs the writing instruction. Furthermore, the design projects are chosen such that they increase in complexity and duration, allowing students to master certain design skills before moving on to other skills.

When the changes discussed above were implemented in the SEC sequence, the faculty were able to observe measurable improvements in the students perception of the course, the final designs for the hoistinator project (as measured by the 2004 performance score) and the written reports in the greenhouse gas reduction project. These observations are discussed in detail by Dahm, *et al.*, [17] and summarized below.

Selected results of course evaluations for the fall 2004 and fall 2005 semesters are summarized in Table 1. The questions reported in this paper are those that are most directly linked to design and writing. These surveys suggest that student perceptions of the course improved as a result of the course revisions.

Table 1: Selected results of student course evaluations

Question	**Mean Response: 5=strong agree, 1=strong disagree**	
	2004	**2005**
This course assisted me in developing teamwork skills	3.82	4.32
This course assisted me in developing multidisciplinary engineering design skills.	3.70	4.06
This course assisted me in developing project management skills.	3.93	4.24
This course helped me make the link between engineering design and writing.	3.89	4.02
Number of respondents	104	108

Student performances have improved as well. A cumulative density function plot of hoistinator performance scores from the fall 2003, 2004 and 2005 semesters is shown in figure 5. The fall 2005 semester was the first year that was taught with the revised design content. To ensure consistent comparisons, all scores on this plot are using the 2004 performance score. There is a slight improvement in the scores from 2003 to 2004. However, there is a significant improvement in the 2005 scores, even though these students were not aware of the 2004 performance equation. These plots suggests that the revised course resulted in improved student design capabilities.

Student design reports from the greenhouse gas reduction project were evaluated using rubrics that were initially developed to evaluate Junior and Senior Engineering Clinic reports. These rubrics were designed to evaluate key ABET objectives, and have been shown to be objective and repeatable[18]. Reports from spring 2004 and spring 2005, the last year before, and the first year after the changes to the design instruction, were evaluated. The result of these evaluations, summarized in Table 2, suggest that the 2006 reports were better than the 2005 reports in every category that was evaluated. Many of these improvements were statistically significant to a 95% confidence. These results suggest that the improved design instruction led to a sustained ability to write about designs.

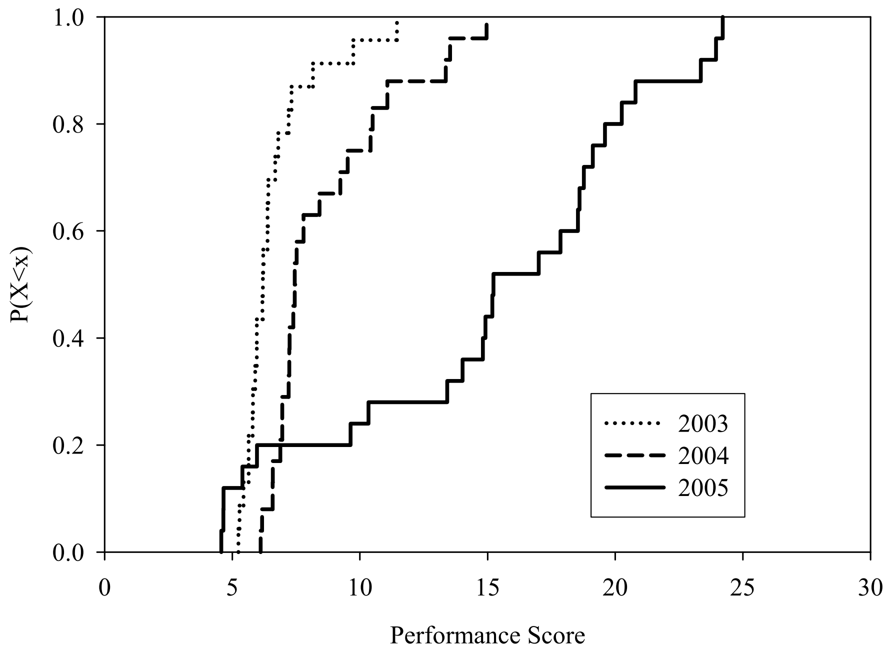

Figure 5. Performance scores for the hoistinator project over a three year span. Significant changes to design instruction were made in 2005.

Summary and Conclusions

Recent efforts to improve design education at Rowan University have been rewarded with documented improvements in the final designed artifacts, final design reports, and student course evaluations. Based on these experiences, the following general recommendations for teaching communication and design are made:

Since design is a difficult subject for students to learn, it should be introduced through simple design projects, and then reinforced with more complex design projects.

Discussing cognitive aspects of design, especially in terms of concrete examples from a project based learning course, helps students to navigate the design process.

When evaluating student performance and the course, it is important to consider both design decisions and the final design.

The most obvious and concrete ways that language can be incorporated into design instruction is by representing designs. However, language can also serve an important epistemic purpose. When student write about the design process, they learn about designing. Finally, for realistic and complete design projects, language plays an essential role in the initial framing of the design problem. All of these role should be incorporated into a project based learning design course.

Finally, it is not sufficient to merely expose students to design problems. Learning design can, and should, be facilitated through a carefully considered pedagogy, just as any other academic subject.

Table 2: Learning outcomes for Sophomore Engineering Clinic II, and mean performance of spring 2005 and spring cohorts with respect to each outcome (4=best, 1=worst).

Desired Outcome	2005	2006
Students demonstrate an ability to apply knowledge of mathematics, science, and engineering (ABET - A).	2.48	3.11
Students approach tasks involving the acquisition and interpretation of experimental results in a logical and systematic fashion. Specifically, students make appropriate measurements, record information in a meaningful format, perform necessary analysis, and convey an interpretation of the results to an appropriate audience.	2.19	2.60
Students design and conduct appropriate experiments that effectively use limited resources to obtain the necessary information.	**2.00**	**2.73**
Students demonstrate the ability to identify, formulate and solve engineering problems (ABET - E).	**2.31**	**2.90**
Students demonstrate understanding of contemporary issues relevant to the field of engineering (ABET - J). Students have an awareness of current technical material (journals, trade publications, web sites, etc.), develop an ability to find relevant current information and use this ability in their curricular assignments.	1.44	2.25
Students have the ability to use techniques, skills, and modern engineering tools necessary for engineering practice (ABET - K). Students apply fundamental principles of engineering to solve engineering problems.	2.17	2.83
Students have the ability to use techniques, skills, and modern engineering tools necessary for engineering practice (ABET - K). Students use the internet and appropriate software packages including spreadsheets, word processors, mathematical packages and process simulators to assist in problem solving.	2.22	2.83
Students have experience in undergraduate research.	**2.28**	**2.94**
Students have the broad education necessary to understand the impact of engineering solutions in a global/societal context (ABET - H). Students draw from their general education and science background to develop engineering solutions that demonstrate an awareness of energy, the environment, business and economics, government, and other global and societal issues.	2.11	2.50
Students demonstrate effective oral and written communication skills (ABET - G). Students will write effective documents including memos, e-mails, business letters, technical reports, operations manuals, and descriptions of systems, process, or components.	**2.04**	**2.83**
Number of Reports	9	12

Boldface indicates that the difference between 2005 and 2006 performance was statistically significant (95% confidence) for that indicator.

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