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A Multidisciplinary, Hands-on, Freshman Engineering Team Design Project and Competition*

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To introduce engineering students to multidisciplinary team work and the principles of engineering design early in their educational careers, a freshman design project and competition was developed. This project and competition required skills typically associated with the four engineering departments (the Departments of Chemical Engineering, Civil and Environmental Engineering, Electrical and Computer Engineering, and Mechanical Engineering) in the College of Engineering at Villanova University. Students were required to build a model car with proper gearing, construct a bridge, and supply power through an electrochemical reaction to complete a specific set of tasks. Teams could only use the limited materials supplied to them. The competition involved an aesthetics contest, a race (including a hill), a load pull, and a load test of the bridge. The project emphasized teaching the freshmen engineering students about team work, open-ended design issues, long-term deadlines, creativeness, the multidisciplinary nature of engineering, as well as the 'fun' of engineering.

Keywords: Multidisciplinary design, first year design, team-based design, hands-on project.

INTRODUCTION

GRADUATING ENGINEERING STUDENTS are expected to operate and function effectively on teams and more specifically multidisciplinary teams [1]. Good team skills are desired and required by science and engineering employers. In a professional environment, teams are observed to increase productivity, reduce time-to-market of new concepts, and to increase profitability gains [2]. In an effort to make them effective team members, undergraduate engineering students are placed on many different teams throughout their educational experience. Examples include formalized homework teams, group project and presentation teams, and capstone design project teams. Also, students are typically required to work on teams in the science and engineering instructional laboratories. However, simply assigning a group project or presentation does not guarantee that the team member will function efficiently, exchange ideas, or share responsibilities. Most engineering curricula do not include formalized instruction on how teams should function or interact [2]. All engineering disciplines recognize the importance of team work, but rely on students figuring it out for themselves along the way.

In addition to graduating with team work skills, all undergraduate engineers are expected to develop the ability to design [1]. Design has been identified as the distinguishing characteristic of the engineering profession [3]. Learning the design process is typically left to a capstone design course near the end of students' educational career [4]. Unfortunately the upper level engineering capstone design courses are often restricted to a specific major, and hence, the multidisciplinary nature of the design course is often limited. Some programs have been able to successfully introduce multidisciplinary design into higher level courses [5–7]. However, more programs are introducing design at the freshman level where specific majors do not yet exist [8–10]. Not only does this help students learn more about the design process earlier, but it may also help recruit and retain engineering students [11]. Several studies [9–13] have found that an exciting, enjoyable, and creative design project focusing on team work in the freshman year can help improve engineering retention and even increase enrollments.

The engineering faculty at Villanova University have redesigned the freshman engineering curriculum to bring more interdisciplinary coursework, teamwork and design into the first year. To accomplish this, a new first-semester project and competition was introduced having the following three major objectives:

- allow students to learn about teamwork;
- have students participate in a multidisciplinary design project;
- and make engineering fun.

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Table 1. Items in the Freshman Engineering design kit

Item	Quantity in kit	Total cost
Lego Mindstorms Robotics Invention System (717 original pieces)	1 kit—one motor, battery/control module, and all sensors removed	$199.99
Craft sticks—large	50—can be modified (cut, drilled, etc.)	$1.10
Craft sticks—small	50—can be modified (cut, drilled, etc.)	$1.00
Machine bolts	60	$2.00
Nuts	60	$1.00
Washers	120	$1.20
Metal corner angles	18	$4.50
Copper strip	12 × 1 × 1/16 inch—can be modified (cut, drilled, etc.)	$1.20
Magnesium ribbon	6 feet—can be modified (cut, drilled, etc.)	$4.50
Connection Wire	2 feet—can be modified (cut, drilled, etc.)	$0.50
UV-Vis Spectrometer Cuvets	20	$2.00
Alligator clips	26	$32.50
Lemon juice	1 quart bottle—can be modified (cut, drilled, etc.)	$1.50
Grocery paper bags	2—can be modified (cut, drilled, etc.)	free
Table salt	not in kit—as much as you want	
Deck plate for bridge	not in kit – use any cardboard	

PROJECT DESCRIPTION

At the beginning of the semester, each student was assigned to a 7 or 8 member team according to their section of the Introduction to Engineering course. Each team was given one kit containing the required materials for the semester long project. The kit materials and associated costs are shown in Table 1. The total cost of the kit was $247.29.

Students were not allowed to use any items not contained within this kit, but could replace parts if they were broken, altered incorrectly, or consumed. They could also paint or decorate any part (except the Lego Mindstorm components) as they wished as long as it did not add to the engineering performance of their final design. At the end of the competition, all Lego components, nuts, bolts, washers and corner brackets were returned for reuse. With the recycling of these items, the recurring cost per year for each kit is only $44.30.

Each team was asked to build a vehicle to traverse the course shown in Fig. 1. There exists a 21-inch gap to cross in the course. To span this gap, the students needed to construct a Warren bridge type truss from craft sticks or other material supplied in their kit. There were five guaranteed 'A's for the project. The team would receive an 'A' if their car completed the course shown in Fig. 1 and it won one of the four following competitions: a race for the fastest time to complete the course, a judging of the aesthetics of the vehicle and bridge, a load pull to see which vehicle could pull the most weight, and a bridge load test to see which bridge could support the most weight before failure. An 'A' would also be given to the team that finished first overall (based on a composite ranking system of the four individual competitions). Each team whose vehicle and bridge designs were capable of meeting all goals (specific race time, minimum load pull, and minimum bridge loading achieved) also received an 'A'. A 'B' was given to those teams whose vehicle and bridge design was capable of meeting most of the goals. A 'C' was given if only one of the desired goals was achieved and a 'D' was given if the vehicle and bridge could not meet any of the goals but the team at least attempted to do so.

TECHNICAL INSTRUCTION

The Introduction to Engineering course documented in this report had nine sections of 27–33 students each. Each section met for two 50-min lectures and for a 2.5-hr laboratory each week. A

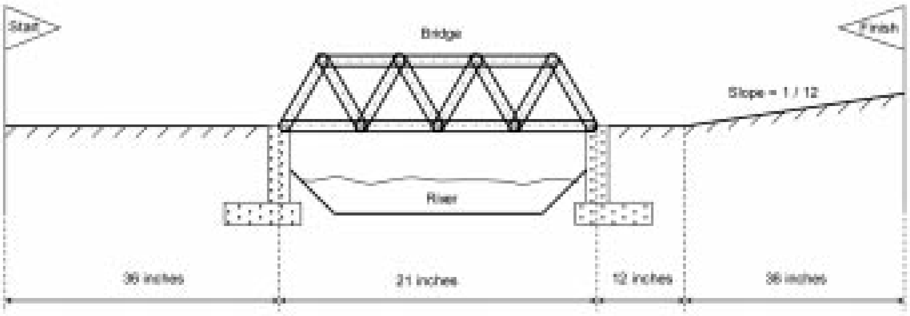

Fig. 1. Course for competition with all dimensions given in inches. Width of the course is always at least 24 inches. Students needed to supply the bridge.

primary instructor for each section taught the majority of the course content. The course topics included computer graphics, simple problem solving, spreadsheet applications and general engineering analysis. Each of the four engineering departments (Chemical, Civil and Environmental, Electrical and Computer, and Mechanical) assigned an additional instructor to teach two lectures as well as one laboratory session for each section. The goal of the first lecture was to introduce the freshmen to the respective engineering discipline and provide information to assist in selecting their major. Villanova has a common freshman year for engineering and we have found that about 24% of our students change their engineering major from the time they enter the program until the beginning of the sophomore year. The second lecture was designed to cover the discipline-specific technical information required as background for the project. Chemical Engineering discussed electrochemical reactions and specifically explored the use of copper, magnesium, and an acid (citric acid in lemon juice) for the construction of an electrochemical cell to generate the electricity necessary to power the motor in the Lego kit. The concept of rates of reaction, the factors influencing reaction rate, the voltage, amperage, and power of the electrochemical cell, as well as series and parallel configurations for the cells, were discussed. Civil and Environmental Engineering covered truss and bridge designs. Concepts related to construction of free body diagrams, external and internal forces, stresses, equilibrium, two force and multiforce members, and basic load-deformation behavior were illustrated within the context of bridges. Electrical and Computer Engineering discussed good electrical connections, resistances in circuits, and more information on parallel and series circuits. Finally, Mechanical Engineering lectured on electrical motors, torque, gearing, and factors influencing a stable mechanical design. Granted with only one lecture, these topics were not covered in depth, but rather the introductory background was given so that students could explore more on their own to enhance their knowledge.

Although lectures and discussions in the classroom have been the traditional method for passing along concepts to students in the hopes they retain and comprehend information, active learning mixed with group learning has often been shown to be more effective [14–16]. We have confirmed these findings with our own surveys of upper class students. Five classes were recently given a survey and asked to rank which parts of a course they thought helped them to learn and understand concepts the best (5 = best, 1 = worst). The average scores were as follows: 4.9 hands-on experiments, 4.1 multimedia demonstrations, 2.8 lectures/lecture notes, 2.2 homework assignments (non-experimental), 1.2 studying for exams. The students overwhelming felt the hands-on visual experiments were best for their learning.

In order to reinforce the material presented in each department's two lectures, several active learning experiences were incorporated into these lectures. For example, when learning about electrochemical reactions, small groups of students where tasked at balancing several reactions and picking the one that would provide the largest voltage. A two and a half hour laboratory session was also included to further the students' conceptual understanding and practical application of the information presented in these lectures. Each section was divided into groups of three to five students (members of their own design project team) who had to complete a set of laboratory experiments and answer eight to ten questions covering the technical information presented in lecture. These laboratory assignments were factored into the final course grade and weighted equal to a regular laboratory assignment.

TEAMWORK INSTRUCTION

Meyers and Jones [14] developed five criteria required for effective teamwork, shown in Table 2. By following the concepts listed in Table 2, students have been shown to exhibit better analytical, creative, and critical thinking skills [16]. These are the higher-order thinking skills [17] that we strive to have our students master.

Teamwork instruction based upon the requirements in Table 2 as well as other literature in the field [18–19] was given throughout the course by the instructors as well as through informational handouts. While teaching the technical content of the course in lectures and the laboratory, each department instructor would provide helpful hints about the design project and how to accomplish it as a team. Also, in the handout describing the project, each team was instructed to complete several tasks to facilitate effective teamwork as described in Table 2. These instructions are presented in Table 3.

Individual accountability for the project was achieved by assigning a group as well as an individual grade. The individual grade was calculated by prorating the team grade (performance in

Table 2. Meyers and Jones [9] criteria for effective teamwork

1. A sense of interdependence among the team members: all members must rely on one another to achieve specific goals.
2. Individual accountability: all team members are held accountable for both doing their share of the work as well as for understanding the complete final project.
3. Frequent face-to-face interaction: some of the work must be done interactively with members providing feedback and guidance.
4. Appropriate use of interpersonal skills: members should use leadership, communication, and conflict resolution skills.
5. Critical analysis of the team progress: goals and timelines must be set and analysis of progress must be made on a regular basis.

Table 3. Specific instructions given to groups about teamwork.

1. Assign tasks to each team member with a team leader to coordinate tasks. For instance, you might have a bridge building team, a vehicle construction team and a power generation and control team each with a leader, as well as an overall team leader. Sub-teams should keep in constant contact as everything must work together in the end (i.e. vehicle fit through the bridge, power supply fit on the vehicle, etc.)
2. Planning is vitally important. You do not have much time and the time will go quickly. Set intermediate deadlines for your team and stick to them. For instance, you could set a deadline to have a bridge and a vehicle that works with batteries by Oct. 20th, and a working system by Nov. 10th. It is recommended that you use 2 or 3 AA batteries to practice with your car as some of the chemicals provided will be consumed during tests so you have to ration these supplies.
3. Keep on schedule. Make sure each task is complete before moving to the next step. Start simple and gradually make your vehicle quicker and more reliable. Work out all problems with one function before adding another.
4. Name your vehicle. It personalizes the project.
5. Ensure your vehicle works reliably before the competition date. For instance, you may want to have your vehicle complete the practice course successfully **at least ten times prior to the competition**.

the competition) according to the 'Time and Effort Analysis' each team member submitted. Members of the teams provided an honest assessment of the efforts made by individual team members in the various phases of the project. The phases included in this assessment are Planning, Design, Construction of Vehicle, Construction of Bridge, Construction of Power and Circuit, Testing and Revision, and Miscellaneous. The number of hours each person in the group spent on each of these topics is totaled. The team grade would then be multiplied by an adjustment factor to determine each person's individual grade based upon the relative amount of time each member spends on the project. The multiplication factor was the hours the individual member spent on the project divided by the average hours spent by a member on the team. This adjustment factor method was based upon work by Brown [20] which shows that individual accountability in grading actually enhances teamwork performance. It was important that each person in the group signed this document indicating that it was a fair assessment of their work. It was also important that this document be submitted regularly throughout the project so nobody was surprised in the end by the group's assessment of an individual's work. With regular team assessment, any difficulties in team dynamics would be brought to the professor's attention as soon as possible (although in the first year none were reported). This type of assessment of individual effort in group projects has also been successfully used in a number of our upper level courses.

MULTIDISCIPLINARY DESIGN

This project and competition required students to utilize skills associated with each of the four engineering disciplines offered at Villanova. It was truly a multidisciplinary project requiring all of the discipline-specific skills to be used together in order to accomplish the competition goals. Teams were assigned at random but team members were kept in the same section of the class. As an example, the discipline makeup of each team in one section of the course is shown in Table 4. It was possible for teams to be lacking in members of a specific discipline; however, only three teams of the 36 actually had less than the four disciplines represented.

The project also had various essential elements of the design process build into it. Students were expected to have setbacks and failures along the way that required their team to learn from these experiences and overcome their difficulties. Failure is unfortunately a common reality in design projects, and team responses to intermediate failures often determine the final outcome. There were also minor imperfections in both the construction materials and the course. Some of these imperfections included cracks in craft sticks, bolts of varying sizes and weights, and small bumps and imperfections in the course. No design situation is ever ideal. This experience was intended not to be a 'textbook homework problem' with a neat and easy answer. The best designs were those that were able to minimize the effects of any imperfections and accomplish the 'mission goals' with the constraints of time and the limited materials made available.

For the overwhelming majority of the students in the class, this project was their first experience with an open-ended design project where there was not a single obvious best choice of design parameters. The students were required to experimentally test their designs and learn from the results in order to make their vehicle go faster and/or pull more weight and allow their bridge to support a higher load. There were significant trade-offs in the

Table 4. Team member composition of section 001 of the course

Team	Chemical	Civil and Environmental	Electrical and Computer	Mechanical
Ford	1	1	3	2
Subaru	1	2	1	3
Ferrari	2	2	1	2
Mercedes	2	2	1	3

design. For example, students could get more power by using more electrochemical cells; however, this required the vehicle to carry more weight and often be larger which could slow it down. Another trade-off students discovered was in the gear ratios. Getting more speed on the flat part of the course was often in conflict with making it up the hill and the optimal gear ratio needed to be determined to obtain the maximum average speed over the entire course. Maximizing the speed for the race course as well as maximizing the load the vehicle could pull was also not straightforward. The selection of tires (size, tread type, and number of) was another open ended design option. The $Mg + 2H^{+} \rightarrow Mg^{2+} + H_2$ electrochemical reaction also had a lot of possible variations (e.g., surface area of magnesium used, how long to 'prime' the reaction before starting the race, effect of ion build up on the rate, effect of temperature and added salt concentration, and more) which the students had to optimize. Balancing the generation of volts (series) and amps (parallel) by their electrochemical cells also was vitally important. The list of possible design trade-offs is significant and only some are listed here.

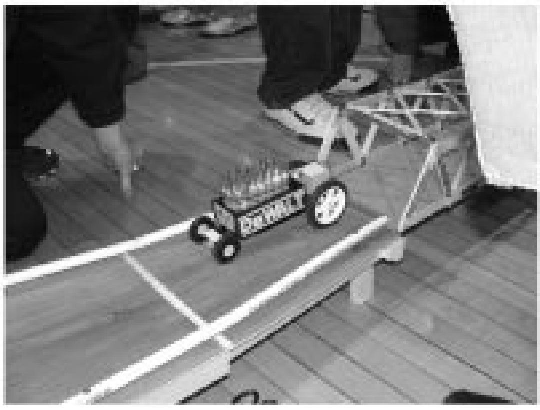

Fig. 3. Team DeWalt completing the race course.

COMPETITION RESULTS

On December 3, 2004 from 2:30–5:00 pm, the First Annual Engineering Freshmen Design Competition in which 36 teams competed was held at Villanova University. All freshmen engineering students were required to attend the competition which was open to the public as well. In groups of six teams, the students would begin the competition at 15-min intervals. At the first event, the aesthetics judging, each team had two minutes to describe their vehicle and bridge to the panel of three judges and answer any questions. After all six teams were judged, they proceeded to the race course and another six teams began the aesthetics judging (this process continued until all 36 teams had completed all competitions). An example of a bridge and car before judging is shown in Fig. 2.

At the race competition, there were six courses set up and each team had a 15-min interval to complete the race course. They were allowed two attempts, with the fastest time counting. A 10-s penalty was added on to the race time if a judge needed to push or nudge the car during the race. A photo of a car completing the course is shown in Fig. 3. After the 15-min race interval, the group of six teams proceeded to the load pull. The teams were allowed to 'refuel' their vehicle if desired. Each team was allowed two attempts (in 15 minutes) at pulling a force meter and the highest value recorded. The final event was load testing of the bridge by applying an eight-inch long distributed load to the center of the deck of the bridge until failure. This was accomplished by suspending a bucket on an eight-inch plank in the center of the bridge (see Fig. 4). Sand and weights were slowly added until bridge failure.

A composite ranking system was used to find the overall winners of the competition. For each of the four individual competitions, a team would receive one point for a first place finish, two points for a second place finish, all the way down to 36 points for a last place finish. The lowest cumulative score would then be the winner of the competition. Team Dodge placed first with 36 points never placing below 18th in any event. In second place was team Mercedes with 40 points. Team Buick finished third with 42 points. The last place

Fig. 2. Example of a finished bridge and car design.

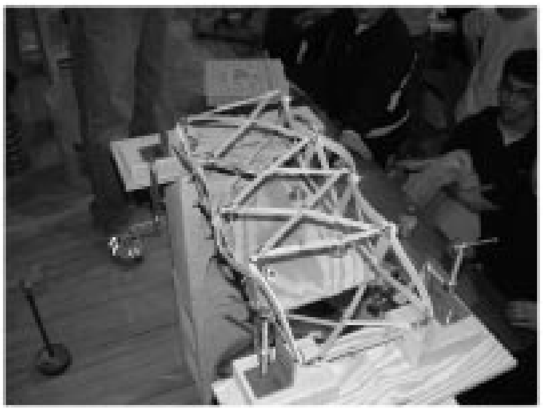

Fig. 4. Bridge buckling under load test.

Table 5. The best, average, and worst score of each competition

Competition	Best score	Average score	Worst score
Aesthetics	57/60	42/60	29/60
Race	3.01 sec	28.73 sec	105.87 sec[a]
Load pull	0.59 lbs	0.24 lbs	0.10 lbs
Bridge test	178 lbs	93.4 lbs	27.4 lbs
Composite score	36	72.4	116

[a] Not counting the one team that did not complete the race course.

team accumulated 116 points. A summary of the best, average, and worst score in each competition is shown in Table 5.

After all four competitions were completed, each team had to disassemble their vehicle and remnants of their bridge. All Lego parts, washers, nuts, machine bolts, and angle brackets were counted and returned. Missing parts had to be paid for by the team. During the 2.5-hr competition, drinks and pizza were provided to the participants free of charge. Cheering and yelling was heard all over the gymnasium as vehicles and bridges competed. A computer projection of the results was constantly being updated so participants and observers could follow the leaders. The school paper covered the event and it made the front page in the issue following the competition. The enjoyment of the students, accomplishing a task which at the beginning of the semester seemed overwhelming, was an excellent outcome of the design competition. Next year we are expecting to invite local media to cover the competition, which will be altered slightly, and it should be reported by the local newspapers as well as by the Philadelphia-based television news stations.

ASSESSMENT, SUMMARY AND FUTURE WORK

The first year of this annual competition allowed freshmen engineering students to improve their ability to function on multidisciplinary teams and to tackle the difficultness and open-endedness of an engineering design project. Specific instruction on teamwork and design approaches were passed along to the students in traditional lecture classes, hands-on laboratory experiments and assignments, as well as through the handouts on and completion of the actual design project and competition. These skills are often not presented in the freshmen year although they are critical to the development of an engineer, as well as for achieving the Engineering 2000 criteria required by ABET.

Through the introduction of a fun, entertaining design competition, students will be better prepared to learn more about engineering and we plan to continue assessment efforts to support this in the future. We also hoped student retention in the engineering program would be higher with the inclusion of practical, design-based education in the freshman year and the first year retention data has been notably higher. Historically 84% of our freshmen engineers enroll in the sophomore year in engineering. At the time of registration for the Fall 2005 semester, 91% of our freshmen are remaining in engineering. The only significant change to the freshmen curriculum has been the addition of the design project and competition.

Table 6. Summary of student responses to question about teamwork and design before and after the competition

Statement	Before	After
I have an awareness of what graduates of each of the disciplines of engineering at Villanova do after graduation.	61%	96%
I have experience working on multidisciplinary teams.	43%	100%
I have knowledge of how teams should function effectively.	61%	91%
I have experience working on a design project.	35%	100%

To further our assessment of this project and competition, we chose to interview about 10% of the freshman class (23 students) concerning their views both before and after the course and competition. Our goal was to obtain data about the design project and competition and see how it was perceived by the students. A summary of the results is shown in Table 6. From student responses after the class it is clear that the objectives of the project were met. Students walked away from their first semester of engineering with a better understanding of all the engineering disciplines, an experience working on a truly multidisciplinary project, better ideas of how to function on teams, and experience at an open-ended design project.

Besides continually assessing and improving this project, our future plans also include slight revisions to the project for next year. We wish to keep the premise the same, but alter the specific competition slightly so that it will have components significantly different from year to year. Although the project is only in the early stages, we believe its dissemination at this time is vitally important as the incorporation of this project was a direct result of the advice of our College of Engineering's advisory board. The board members, consisting of mostly executives from engineering companies large and small, have stressed the importance of adding more teamwork, interpersonal skill development, and problem solving instruction and assignments in the undergraduate curriculum. These are skills that significant employers of engineers wish to see more firmly developed in the entering workforce. The freshman engineering design project and competition presented here is an excellent start at meeting the goals set forth by our advisory board and we believe it can be easily adopted by engineering programs throughout the world.

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