AC 2007-105: A STUDY OF CHALLENGE-BASED LEARNING TECHNIQUES IN AN INTRODUCTION TO ENGINEERING COURSE

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A Study of Challenge-based Learning Techniques in an Introduction to Engineering Course

Abstract.

The purpose of this study was to determine if there existed a difference in student learning by using challenge-based learning methods over traditional lecture methods in a setting beyond the biomedical engineering based studies that have already been completed. This study was conducted in the first half of ES140 – Introduction to Engineering, which is a required class for all entering freshmen with an enrollment of approximately 310 students. This study continues to apply concepts and materials compiled by the NSF-funded VaNTH-ERC applied to a general engineering course. There were eleven sections of this course taught in the Fall 2006 semester. About half of the teaching faculty taught using traditional methods employed for the past three years as a control group and the other half of the teaching faculty used methods provided by the VaNTH-ERC as an experimental group. Our first goal was to show that students learn more and can adapt their knowledge to various situations better using challenge-based learning methods than traditional lecture-based methods. Our second goal was to demonstrate that students taught in the challenge-based style were better able to articulate their understanding of the strengths and weaknesses of the various computing modalities and when to apply these modalities to various analysis problems.

All eleven sections of this course were required to teach the topics of descriptive statistics, graphing and analysis, and matrix operations using each of the three techniques: paper and pencil, Excel, and Matlab. The control sections of this study moved linearly through these topics with teachers using their traditional teaching methods. The experimental sections of the study began the course with a grand challenge focusing them on determining the strengths and weaknesses of the different tools and computer software engineers might use. Instructors then introduced three challenges that helped students learn the content goals listed above for the course in addition to focusing continually on the strengths and weaknesses of the tools and computer software packages.

Three types of data were used in this study: survey responses, answers to test questions, and reflective responses. The surveys were required of students in all eleven sections of this course. These surveys were completed on-line and submitted to a database. The reflection activity consisted of short, open-ended questions asking students why they chose to use either paper and pencil, Excel, or Matlab to solve each of the mid-term exam questions. Blinded mid-term exams were scored by a grading rubric and compared statistically. The construction of the rubric used for comparing the test results and the reflection assignment focused on how students set up problems and adhered to the problem solving process presented in the class. Further, the decision on which computing modality chosen was examined by asking students to justify their

choices. The rationalization of this choice exposed the students' understanding of attributes of each computing tool and how those attributes related to the problem being solved.

Introduction and Problem Statement.

The purpose of this study was to determine if there was a difference in student learning by using challenge-based learning methods over traditional lecture methods in a setting beyond the biomedical engineering based studies that have already been completed. This study was performed in the first half of ES140 – Introduction to Engineering, which is a required class for all entering freshmen at Vanderbilt University with an enrollment of approximately 310 students. This study was a continuation of the application of concepts and materials compiled by the NSF-funded VaNTH-ERC as applied to a general engineering course.

The Vanderbilt-Northwestern-Harvard-MIT Engineering Research Center for Bioengineering Educational Technologies (VaNTH ERC) is funded by the National Science Foundation (NSF EEC 9876363) as one of the several engineering research centers. Much of the work done in VaNTH has been based upon the text, *How People Learn* (HPL)[1].

HPL learning theory incorporates four "centerednesses" that work synergistically to optimize learning. When these four are in place, studies show that students increase both their content knowledge and their ability to apply that knowledge in new situations – i.e., their *adaptive expertise*[2-6]. First, the learning environment must be *knowledge-centered* -- appropriate information should be presented in an appropriately sequenced and organized way. Second, the environment must be *student-centered* -- lessons should seek out students' prior conceptions and misconceptions, help students make connections with prior knowledge, and be relevant to students' own lives. Third, the learning environment must be *assessment-centered* -- it should include opportunities for formative feedback for both students and instructors: students benefit from opportunities to check their own understanding and instructors from opportunities to assess the effectiveness of their teaching. Finally, a learning environment must be *community-centered* -- students should be provided opportunities to learn collaboratively.

According to HPL theory, students learn best when (1) presented with organized information that (2) relates in some way to their own experiences, and they are given the opportunity to (3) test themselves on their own understanding and to (4) work to develop their understanding with other students. The Legacy Cycle incorporates these four influences on learning by providing a rich, contextually based problem, relevant in some way to students' lives, and allowing students to engage deeply with that problem in ways that include opportunities for collaboration with other students and for self-assessment.

The design utilized in the curriculum modules that incorporates HPL theory[7] makes use of a strong contextually based "Challenge" followed by a sequence of instruction where students would attempt to "Generate Ideas" (first thoughts on the challenge), and view "Multiple Perspectives" of others commenting on the challenge and possible ways to address it. Students then participate in extended "Research and Revise" activities where data and information would be gathered to help the student address the challenge, followed by "Test your Mettle" a formative self-assessment and "Going Public" where students solutions would be made public to peers and

others. While having been implemented in a limited, but growing, number of K-12 studies[2-3] results were positive for students working with this design, referred to as the "Legacy Cycle", by the developers.

The VaNTH Engineering Research Center (ERC) has done numerous studies over the last seven years proving the efficacy of the challenge-based teaching method at both the high school and college levels. The success of these studies includes students mastering the basic course content better in challenge-based classrooms than in traditional teaching methods classrooms. Students have also been shown to be able to transfer their new knowledge to other relevant situations more readily in challenge-based learning. Success at the high school level (only a few months removed in age from these college freshmen) has been shown by Klein and Sherwood[3]. Success has also been demonstrated at the collegiate level in numerous publications[4-6].

Our first goal was to show that students learned more and adapted their knowledge to various situations better using challenge-based learning methods than traditional lecture-based methods in an introductory multi-disciplinary engineering context. Our second goal was to demonstrate that students taught in the challenge-based style were better able to articulate their understanding of the strengths and weaknesses of the various computing modalities and when to apply these modalities to various analysis problems. Introduction to Engineering is currently taught in eleven sections to incoming first-year students at Vanderbilt University. The introductory course in engineering was remodeled several years ago to satisfy new course goals of fostering early and informed student decisions regarding their declared majors, bringing real world engineering problems into the classroom, and anchoring the curriculum in the context of engineering problem solving.

Towards achieving these goals, learning objectives were defined and a model for implementation designed. The learning objectives are (1) to educate the students to apply the problem solving processes essential in solving both design and analytical problems, (2) to enable the students to solve these problems using engineering computing tools while continuing to use the process and (3) to allow them to make educated choices on the use of appropriate tools for the appropriate problems. A modular course implementation system was designed to accomplish both the global as well as specific goals for the students. The semester begins with a general module where basic computing and problem solving skills are developed and the problem solving process emphasized. This module encompasses the first half of the semester and is the driving force of the semester. The general module is taught in the context of data management/analysis using different software packages. Based on these skills, discipline-specific modules were created for each engineering major offered at Vanderbilt. The student proficiencies at the end of module 1 form the foundation in the development of the subsequent modules and are based on the problem-solving methodology in a discipline-specific environment. Thus, the second half of the semester consists of two self-selected four-week, discipline-specific modules focused on a current event or area of research. Each discipline-specific module is designed in the context of problem based learning with a fundamental set of criteria and deliverables, which include a grand challenge statement, a culminating activity/deliverable, a minimum of three assignments that apply the concepts of problem solving learned in module 1, oral presentations, design and technical writing amongst others. The discipline-specific modules allow students to apply

concepts of problem solving in an interesting and challenging setting during the second half of the semester.

The modular course approach was designed to increase student-faculty interaction and to optimize student interaction with faculty from the engineering departments of their choice. It is our conclusion from a previous study that the changes we designed addressed students' needs and facilitates their academic goals. These changes provided students with the opportunity to identify with what it means to be an Engineer and being a part of the engineering community (at Vanderbilt) through exposure to practicing engineers, engineering faculty, graduate students, and fellow undergraduate students, to understand the focus of each (selected) engineering major and then be able to make an informed choice and to begin building professional relationships with faculty members within the student's department of interest[8].

Experimental Methods.

Of the eleven sections of this course taught in the Fall 2006 semester, seven of the teaching faculty taught using traditional methods employed for the past three years as a control group and four faculty members used methods provided by the VaNTH-ERC as an experimental group. The test subjects were a random sample of students from the approximately 310-student freshman class primarily 18 years or older. Three types of data were used in this study: survey responses, answers to test questions, and reflective responses.

All sections of this course were required to teach the topics of descriptive statistics, graphing and analysis, and matrix operations using each of the three techniques: paper and pencil, Excel, and Matlab. The control sections of this study moved linearly through these topics with teachers using their traditional teaching methods. The experimental sections of the study began the course with a grand challenge focusing them on determining the strengths and weaknesses of the different tools and computer software engineers might use. Instructors then introduced three challenges that helped students learn the content goals listed above for the course in addition to focusing continually on the strengths and weaknesses of the tools and computer software packages.

The grand challenge shown below encompassed the ultimate overarching concept we wanted the students to grasp.

> *Grand Challenge*
> Since problem solving is an extremely important part of engineering study and engineering practice, you must be familiar with the problem solving tools available to you. You must also know when and how to use them correctly and efficiently. What tools and computer software might engineers use in the *process* of problem solving and what are their strengths and weaknesses?

The primary assessment tool for the Grand Challenge was the mid-term exam. Results of this assessment are identified in the next section. The individual challenge questions are shown below. These challenges were graded as regular homework assignments. The solutions to these

challenges were submitted in a lab report format with solutions worked in Excel and Matlab. Students also had to explain what the strengths and weaknesses were for each modality used.

Challenge #1

The data table below gives the life expectancy in years for a child born in the given year.

Year	Life Expectancy
1900	47.3
1915	54.5
1930	59.7
1945	65.9
1960	69.7
1990	75.4

1. Create a plot of the data.
2. Do the data appear to be linearly related? Add a trendline and find the correlation coefficient.
3. Plot the data on semi-log paper. Interpret the results. Find the line of best fit for this plot and the correlation coefficient.
4. Which curve appears to fit the data better? Why?
5. Use each model to extrapolate the life expectancy for an infant born in 2006.
6. Use the Internet to research a life expectancy value for 2006. Cite your resource. How does this value compare to the two models' prediction? Why are they similar or dissimilar? Does the better model more closely predict your researched value?

Challenge #2

A new sewage treatment plant in Franklin, Tennessee recently went online. The effluent (treated wastewater) is discharged into the nearby Harpeth River. The EPA is conducting an environmental impact study of the new plant. As part of the study, they're measuring the temperature of the river downstream. The attached file, harpeth-temps.txt, contains the results of these measurements from a recent month. You have been asked to make the following analyses:

1. Provide descriptive statistics on the population.
2. Create a random set of three sample populations containing 10, 20 and 50 data points respectively. Describe the statistics of the sample for each. Your random samples should be computer generated.
3. What is the percentage error for each sample mean and variance in comparison to the population?
4. Plot histogram for the population and each of the sample data sets and compare their distribution.
5. If you were to submit your findings to the EPA, which set of data would you use for your calculations?

Challenge #3
One of the most common chemical reactors found around us is the car engine. It takes gasoline and reacts it with air to release chemical energy, which in turn is transformed into mechanical energy. Emissions from your car's engine have been an environmental concern for many years.

Using the concepts of material balances, determine how much (in moles and lbs) air is needed and CO_2, N_2, CO, and H_2O are emitted for every gallon of gasoline burned in your car's engine. Assume that gasoline, a mixture of many hydrocarbons, can be modeled as pure octane (C_8H_{18}). Assume that 90% of the octane is turned into carbon dioxide and water, and 10% of the octane is turned into carbon monoxide and water. No excess air is involved in the reaction, meaning only enough air to provide the needed oxygen is introduced into the engine. Also assume the nitrogen in the air does not react at the temperature of your engine. Use the variables nO_2, nN_2, nCO, nCO_2, nN_2, and nH_2O to represent the number of moles of each component in various streams.

Students in all eleven sections completed two surveys in the test semester; a pre-course survey a post-course survey. All students took a mid-term exam at the completion of module 1 which was used in the analysis. This exam was comprised of three problems. The first problem asked the students to explain statistical concepts about sampling, compute measures of center, spread, and variance, and use concepts about normal distributions. The second problem was a mass balance problem that required the student to solve a matrix problem. The third problem required students to appropriate plot data, fit a curve to that data, and use that model to make an interpolation. All student exams were taken on their individual laptops and submitted electronically for grading. Exams from every fifth student in each section (students #1, 6, 11, 16, 21, 26 when alphabetized) were used for analysis. Each student's name was removed by the instructors and submitted for analysis. The blinded exams were scored by a grading rubric and compared statistically.

The reflective survey was required of students in all eleven sections of this course. This survey was administered as a participation-only, post-exam assignment. This reflection activity consisted of short, open-ended questions asking students why they chose to use paper and pencil, Excel, or Matlab to solve each of the module 1 exam questions. The reflective survey assignment sheet is shown in the Appendix. The rationalization of this choice should expose the students' understanding of attributes of each computing tool and how those attributes relate to the problem being solved.

Pre-course and post-course surveys were used to assess students' impressions of their competencies before and after the course. Students were asked to self-assess their ability to solve problems with the assistance of the software modalities and their comfort level with using computers.

Statistical analysis was performed using SPSS (v14). Test questions and reflection assignments were compared using an independent samples t-test. When pre-course survey data was available for a particular survey question, it was compared with the post-course survey data using an ANCOVA analysis holding the pre-course survey as the covariate. Independent samples t-test

was used when only post-course data was available. Statistical significance was determined to have been met when the p-value was below 0.05.

Results.

Survey

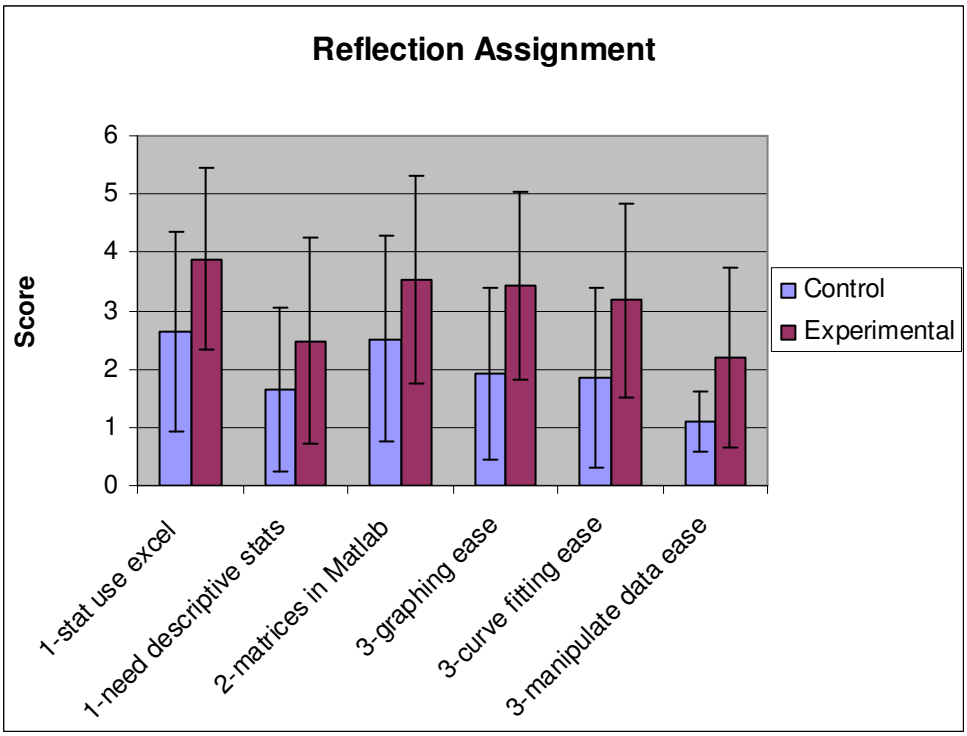
With the exception of one question, no significant differences were found between the control and experimental groups in the survey data. The control group (n=90) reported a higher level of comfort with computers (4.26±0.65) as compared to their pre-course survey than did the experimental group (n=54; 4.13±0.85) (p=0.012).

Midterm Exam

The midterm exams collected were evaluated using the scoring rubric described above and shown in the appendix. The vast majority of the test problems showed no statistically significant differences between the control and experimental groups. The majority of the differences observed between the two groups lie in the first question requiring students to explain and use statistical measures. Experimental group students (n=24, 4.58±0.65) were better than control students (n=30, 3.71±1.36) in displaying an understanding of sampling through explanation of sample vs. population assumptions (p=0.005). Experimental group students (4.79±0.66) were also better than control students (4.17±1.26) in displaying an understanding of measures of center through correctly choosing and calculating these measures (mean, median, mode) (p=0.024). Lastly, the experimental group students were better than control students in displaying and understanding a measure of spread through correctly choosing and calculating either range or standard deviation of the data set (4.92±0.28 vs. 3.90±1.45) (p=0.001). On the second problem on mass balances, the experimental students were more likely (p=0.044) to compute a correct final answer than the control students (4.58±1.06 vs. 3.83±1.58).

Reflection Assignment

No differences were found in the students' ability to determine the best modality to use for each exam problem. Large differences were found in the students' ability to articulate why they chose one modality over another. From the reflection assignment, all of the questions asking the student to articulate why their modality choice was the best one resulted in statistically significant (p<0.001) better responses from the experimental group (n=94) than from the control group (n=107).



Discussion of Results.

From the results shown above, an outcome from the pre- and post-course surveys is the lack of difference in competence level of the control and experimental groups. Students were asked to rate their skill in using Excel and Matlab, their comfort level with using computers, and their computer savvy before the course began and at the end of the semester. Both control and experimental groups used computers the same amount throughout the first module of the course. Homework problems were identical and the number of problems assigned was identical. It is not surprising that the two groups responded in the same manner.

The control group responded as being more comfortable using computers than the experimental group. A possible explanation for this outcome is that the experimental group may have had more knowledge of computing systems and realized how much they do not know. The experimental group was asked to articulate their problem solving process three more times using the Legacy Cycle than the control group. With this higher frequency and detail of explanation required, the experimental group may have realized the difficulty in explaining each step of the process.

Both groups also produced similar results on the mid-term exam given at the end of module 1. It is actually a positive result that the two groups performed similarly on the exam. The exam was designed to test the problem-solving skill of the students in solving engineering problems; therefore, similar results demonstrate that both groups became similarly competent in their problem solving skill. It is also a positive result that neither group achieved lesser competency, thus putting them at a disadvantage with their peers. On the exam questions that asked students to explain some concept such as random sampling, the experimental group demonstrated a

greater ability to articulate the virtues of random sampling. They were also better at performing a statistical analysis than the control group. A possible explanation for this outcome could be that statistical analyses typically are more interpretive and require a greater amount of explanation than some traditional analysis-type problems engineering students tend to see the most.

The reflection assignment provided the most interesting results of this study. The experimental group was significantly better at articulating their reasoning in selection of specific computing modalities than the control group. Since the experimental group was subjected to the challenge-based learning method, they had more experience with stating various parts of the problem solving process. The experimental group submitted solutions to three sub-challenges which asked them to articulate and interpret their results to open-ended problems. While the control group also had some exposure to open-ended problems, the experimental group was guided by a more formal process. Additionally, the experimental group followed the Legacy Cycle three times in the first half of the semester whereas the control group did not. The Legacy Cycle required students to form their own ideas at the beginning of the cycle; these ideas are then modified through the research and revise stage and reported on in the go public stage. Requiring students to be more thoughtful about their own understanding of why you choose a computer software tool seems to have contributed to their ability to articulate their reasoning. The significance of the results solidifies the assumption that even a small amount of exposure to this learning method produces more positive results.

Conclusions.

While we were unable to measure widespread differences in the amount learned based on a single mid-term exam, the experiment was successful in demonstrating that the Legacy Cycle as applied to a course such as this improves the communication ability of first-year engineering students. Such a significant portion of engineering problem solving involves the communication and interpretation of the solution. Because of this reasoning, articulation of all aspects of the problem and justification of computing methods used to solve the problem is essential in training successful, high-quality engineering students. This skill should be introduced to new engineering students in addition to computing and problem solving methods so they will continue to use these methods in upper-level engineering courses. Ultimately, these students will persist with a greater ability to communicate their work at all levels leading to more successful engineering graduates.

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Appendices.

Student: _____

Midterm Rubric

Question 1

a) What assumption is made about the statistics of a random sample compared to the statistics of a population? How does sample size affect this assumption?

Student displays understanding of sampling through explanation of sample vs. population assumptions	1 2 3 4 5
Student displays understanding of sample size through explaining the value of a larger sample size	1 2 3 4 5

b) Report 3 *measures of center*, 1 *measure of spread*, and 1 *measure of variance* for the provided data.

Student displays understanding of a measure of center through choosing 3 correct answers	1 2 3 4 5
Student displays understanding of a measure of spread through choosing a correct answer	1 2 3 4 5
Student displays understanding of a measure of variance through choosing a correct answer	1 2 3 4 5

c) If the distribution of the Color Analysis Score for the population of yellow dye production is considered normally distributed, then 95% of the batches should fall within what C-score range? Using 95% as the product specification, which of the following batches, if any, will need to be trashed?

Student displays understanding of a normally distributed data through calculation of 2 std dev interval	1 2 3 4 5
Student displays understanding of a 95% interval through eliminating correct batches	1 2 3 4 5

Question 2

Write material balances for water, THF, toluene, and xylene, and solve them simultaneously to determine the mass flow rate of streams V_1, L_1, V_2, and L_2. Remember that a material balance is simply a mathematical statement that material going into a process has to come out again. (This assumes a steady state and no chemical reactions.)

Student recognizes that this is a matrix problem	1 2 3 4 5
Student displays understanding of a initial conditions through computing the initial kg/min for each of water, THF, toluene, and xylene.	1 2 3 4 5
Student writes the mass balance equation	1 2 3 4 5
Finds the inverse of the output stream matrix	1 2 3 4 5
Computes V1, L1, V2, and L2 using matrix math	1 2 3 4 5

Question 3

Plot the data in the proper form and find A, $\Delta H_0/R$, and k at 420 °K.

Recognizes the need to compute 1/T for the exponential function	1 2 3 4 5
Plots data in a scatter plot	1 2 3 4 5
Does a best-fit curve	1 2 3 4 5
Displays equation to model	1 2 3 4 5
Uses model to find A	1 2 3 4 5
Uses model to find $\Delta H_0/R$	1 2 3 4 5
Uses model with A, $\Delta H_0/R$, and x=1/420 to compute k for T=420	1 2 3 4 5
Uses correct units on all answers	1 2 3 4 5

Reflection Activity Rubric

1.
Did they choose the best modality?
- 2 – Excel
- 1 – Matlab
- 0 – Calculator

Would they change their mind?
- 6 – correct modality and would not have changed
- 5 – less correct modality and would have changed
- 4 – worse modality and would have changed
- 3 – correct modality and would have changed
- 2 – less correct modality and would not have changed
- 1 – worse modality and would not have changed

Recognizes ease of descriptive statistics in Excel over Matlab or a calculator.
- 5
- 4
- 3
- 2
- 1

Understanding that descriptive statistics should be provided in this problem.
- 5
- 4
- 3
- 2
- 1

2.
Did they choose the best modality?
- 2 – Matlab
- 1 – Excel
- 0 – Calculator

Would they change their mind?
- 6 – correct modality and would not have changed
- 5 – less correct modality and would have changed
- 4 – worse modality and would have changed
- 3 – correct modality and would have changed
- 2 – less correct modality and would not have changed
- 1 – worse modality and would not have changed

Recognized ease of matrix math in Matlab.

5
4
3
2
1

3.

Did they choose the best modality?

2 – Excel
1 – Matlab
0 – Calculator

Would they change their mind?

6 – correct modality and would not have changed
5 – less correct modality and would have changed
4 – worse modality and would have changed
3 – correct modality and would have changed
2 – less correct modality and would not have changed
1 – worse modality and would not have changed

Recognizes the ease of graphing in Excel over Matlab.

5
4
3
2
1

Recognizes the ease of curve-fitting in Excel over Matlab.

5
4
3
2
1

Recognized the ease of graphical manipulation in Excel over Matlab.

5
4
3
2
1