A PROJECT-BASED APPROACH TO FIRST-YEAR ENGINEERING CURRICULUM DEVELOPMENT

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Abstract *– First-year engineering curricula are vitally important in improving the quantity and quality of engineering graduates. Many innovative approaches to first-year engineering curriculum development have been created and implemented over the past twenty years. Often, innovative approaches incorporate one or more engineering projects as learning experiences for first-year students. Further, problem-based and project-based pedagogical theories have offered the framework for many innovative learning experiences for engineering students in all four years of engineering curricula. As Texas A&M University improves its first-year engineering curricula, faculty members are re-examining the nature of the project-based learning experiences both to improve the learning experiences and to develop specifications for future project-based learning experiences. This paper presents the rationale behind the five specifications and offers experiences in developing and implementing the design projects for the prototype first-year engineering curricula. The paper also describes the assessment and evaluation plan as well as assessment data that has been analyzed to date.*

Index Terms —first-year curriculum, design, integration

INTRODUCTION

First-year engineering curricula have been identified as significant opportunities for improvement in four-year curricula, and many institutions have addressed the opportunity in different ways. At Texas A&M University (TAMU), at least four challenges were identified with respect to first-year engineering curricula in the Dwight Look College of Engineering. These challenges are not unique to TAMU and avenues for addressing these challenges might be applicable to other institutions. First, despite the innovations introduced during TAMU's participation in the Foundation Coalition [1], retention of engineering students after one year still requires significant improvement [2-4]. Second, engineering students require clearer understanding of the value and relevance of science and mathematics. Statements made by engineering students at University of California Berkeley characterize student reactions to mathematics and science courses.

> "Well, mathematics is, basically…abstract…unless you apply it to something you don't have a physical foundation… It's more conceptual, you have to be able to manipulate symbols…You got to get over the fact that it may seem pointless, and just do it. That's probably one of the hardest things in math, that there's no reward, there's no tangible physical thing that you have. You didn't find out how far this ball is going to fly, or how long it will take for this thing to cool down. You have a number, and you can't do anything with this number." and

> "The problems in math have absolutely no significance at all. It's purely an exercise." [5]

Third, some engineering faculty members at larger institutions, such as TAMU, generally lack knowledge of the content and student experiences in first-year engineering, science, and mathematics courses. Often to the extent that they are familiar with the content of the first-year engineering courses, they are critical of the content because it has little or no direct relevance for the disciplinary subjects taught by these faculty members. Fourth, students often lack exposure to learning experiences that help them to understand what and how engineers create. Students often fail to grasp the nature of and how their courses are connected with engineering practice. The Engineering Academic Programs Office (EAPO) at TAMU, with the support of a grant from the Science, Technology, Engineering, and Mathematics (STEM) Talent Expansion Program (STEP) program of the National Science Foundation, is addressing these challenges as it renews its first-year engineering curricula.

Faculty members have developed a problem-based [6,7] curriculum for the first-year engineering courses. Students receive 2-hours credit for a course that has two 2-hour meetings per week. About 60% of the class time is devoted to engineering analysis as described below and 40% to engineering graphics—mainly AutoCAD and Solid Works. Building the curriculum around relevant engineering problems helps students connect problems that they can

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recognize and understand to science, engineering, and mathematics concepts that they are learning. In addition to the problem-based format, the project team thought that it was important to develop specifications for problems (or projects) that might be implemented. If specifications that received support across the College could be generated, then any project that satisfied the specifications would address the four challenges. To date, the team has constructed five specifications for project-based learning intended to encourage integration across engineering, mathematics, and physics and to promote faculty acceptance of innovative approaches to first-year curricula.

First, students must be able to plan and predict performance before they build. Projects in which students construct an artifact and then modify the artifact until satisfactory performance is achieved may help develop creativity, but they do not help students to see how the scientific and mathematical concepts that they are learning might be applied to development of their artifact. In fact, students might develop the misconception (e.g., the TV show Monster Garage) that science and mathematics are irrelevant to the engineering design process. To encourage students to see roles for mathematics and science in the engineering design process, the project team thinks that students should be expected to predict how a proposed design will perform before it is constructed and its performance measured.

Second, the project addresses (in a simplified fashion) a societal need that is easily recognizable and relevant to the student's major(s). Engineers, through development and construction of clean water and sanitation systems, have had greater impact on the increase in life expectancy than medical advances in the twentieth century [8]. Engineers help create the technology that supports medical advances. However, many students are unaware of the major role that engineering plays in improving our health systems and society. Helping students connect engineering to people and society builds greater motivation for studying engineering.

Third, students must be able to use the concepts and procedures that they are learning in science and mathematics to predict performance of their proposed design before building. Using mathematics and science concepts that they are learning to predict performance helps students value these concepts. Fourth, students must be able to transfer learning from concept-based courses such as mathematics and science to project-based activities, which form the majority of the engineering design courses. Fifth, projects must promote learning in such a way that engineering faculty members can see connections to efforts to improve student performance in required sophomore-, and possibly junior-, level courses. Engineering faculty value the engineering science courses that they develop and teach. If the learning experiences in first-year engineering courses help students prepare for these engineering science courses, then engineering faculty, who often know little about the workings of these courses, will increasingly value these courses as preparation for their majors. To demonstrate that the set of projects that satisfy the five specifications is not empty, the paper offers the following set of vignettes to illustrate how activities designed to meet the specifications have been implemented.

The overall approach and assessment approach to date has been described elsewhere [9,10]. In this paper, the authors would like to present some specific illustrations of the approaches that have been employed so that readers may have a clearer picture of the innovations that have been introduced and responses from the students.

VIGNETTE NO. 1: INTRODUCTION TO TRUSS DESIGN

On the first day of first-year engineering class, students were organized into four-person teams and each team was given a Supermag® kit of steel balls and magnetic sticks. Each team was asked to build a structure that would span 4.25 in. and support a load. When they had completed their structures, they sketched their structures. Then, on the next day, teams were given a sketch that was not theirs and asked to build the structure from the sketch. Then, they were asked to load the structure until it failed. Finally, students were asked if they thought that building a structure, loading until it failed, and recording the maximum load was the process to be followed to support a specified load.

Faculty teaching the course thought that students learned at least two things from the activity. First, they could see the value of graphical communication because they had tried building a structure from someone else's sketch. Second, students were somewhat taken aback by the question about whether the process they had used was an acceptable process for building structures to support specified loads. Somewhat amazed, they realized that this was not an acceptable process, and more systematic approaches that included predictions of performance were required. Further, predictions often require mathematical models based upon scientific laws.

Data was acquired by giving students a Readiness Assessment Test (RAT) at the beginning of the third class on which students were asked about their understanding of the engineering design process. (In the two first-year engineering courses, a RAT is a 3-5 minute exercise given at the beginning of most classes. It is intended to see if students have prepared for the class.) A large number of the students cited the importance of modeling in the engineering design process. These statements supported the perception of the faculty members that the activity had given students new insights into the importance of models and predictions in the engineering design process. Comments from the peer teachers who talked to the students also confirmed perceptions about student understanding of the importance of modeling in the engineering design process. (Peer

teachers are undergraduate teaching assistants who help students in class and conduct help sessions, but play no role in the grading process.) In the future, faculty members plan to give the same question before and after the activity to ascertain changes in student thinking.

The preceding description focused on the first 2–3 days of class, which were the introduction to a larger project in which students designed a truss from the Supermag® kit and tested it to find the maximum load for comparison to a predicted value that it would support [11]. Later in the truss design project, students were introduced to the analysis of basic co-planar, statically determinate trusses. Reactions were determined from the basic equations of equilibrium: sum of the forces in the x-direction, sum of the forces in the y-direction, and sum of the moments. Forces in the members were determined using the method of joints. Faculty had mistakenly assumed that students were familiar with basic geometry, the basic trig functions and identities, and symbolic, linear algebra. In order for students to complete the analysis process, faculty were forced to spend two class periods on covering basic high-school level mathematics. By the end of the semester most students were up-to-speed on basic mathematics.

VIGNETTE NO. 2: A WHEEL CHAIR LIFT – QUASISTATIC MECHANISM

Students were asked to design a model wheelchair lift to raise a model wheel chair of two ounces through an elevation of two inches in a minimum time of four seconds. The teams were provided Lego® Mindstorm kits with which to build their devices. These kits contain motors, gears, pulleys, sensors, thin beams, and a programmable brick. The constraints were purposefully lax to give the students creative freedom while meeting specific constraints.

Students proceeded to build their devices and then conducted tests to see if they could meet the performance criteria. Students realized that they should not "toss Grandma into the air." Another problem might be that the weight would not move because of misunderstandings about relationships between torque, motor characteristics, and gearing issues. Constraints on the lift were defined so that a quasi-static analysis can be applied. This exercise reinforced concepts of free-body diagrams and equilibrium of forces and moments covered in the truss project.

Students also wrote a Robolab [11] program that would operate the motor as well a couple of sensors. Sensors available to the students for use are a rotation sensor, a touch sensor, and a light sensor. The rotation sensor was used to monitor the motor speed, and the students used the touch sensor to start and stop the motor. Many students equated the use of the touch sensor as a dead men switch.

VIGNETTE NO. 3: INTRODUCTION TO CONSTRUCTION ESTIMATING PROCESSES

Construction cost estimating and scheduling was covered from a systems analysis perspective. For example, students were asked to determine the feasibility of constructing a large parking facility for the engineering complex. The intent was to show students how to simplify a complex problem according to appropriate level of accuracy. In this case we asked them to compare the cost of parking spaces to the expected revenue stream from various rental schemes. The basic intent was to illustrate that "it is better to be approximately right than to be absolutely wrong" when conducting project feasibility studies.

VIGNETTE NO. 4: CONSTRUCTION ESTIMATING PROCESS PROJECT

After estimating the cost of constructing a parking lot, students were asked to estimate the cost and schedule of a street repair project and write an engineering report to document their findings. Students were given specific project limits and tasks to accomplish. Their responsibility was to compute the various quantities of material from field measurements and assumed geometry. Sample means and standard deviations were used to determine overall quality control limits of the measurement, and teams with outliers were asked to repeat their field work.

System simplification was introduced again in order to reduce the complexity to a manageable degree. For example, for "dirt work" plus/minus a dump truck was the standard for accuracy. Despite continued faculty emphasis on estimation and the scale of required estimates, students continued to report answers in "table spoons" of dirt and pennies per square-yard of concrete slab.

VIGNETTE NO. 5: IDENTIFYING THE SYSTEM AND ITS OBSERVABLES

In any modeling or design task, one of the important early decisions is the choice of the system. Following the choice of the system, engineers must determine the observables that are available [12]. A week after the students completed the cost estimation exercise (Vignette No. 4), a RAT was given where the students were asked what they understood by the word "system" and what was the system that they considered for the Ross street project. Generally, the students answered that "a system is a collection of interconnected objects". However, in answering question as to the system that they considered for the cost estimation, students had a wide diversity of opinion as to what formed a part of the system. For example, there were questions such as "why is cost not part of the system?" etc. When it was pointed out that a system component must be a "physical object", one of the students pointed out that "money" was a physical entity. This gave rise to a discussion of the difference between the notes and coins that make up money and the value of money. An example of a parking meter as a system was discussed at

this point, since in this case one of the components of the system was the actual money (in the form of coins) in the parking meters themselves. This was followed by a discussion of the way in which the purpose, task or intent of the designer or engineer played a role in determining the system. For example, in the Ross street project, students were asked about possible systems that the Regents of the University would consider.

It became clear after the end of the class and in talking to the peer teachers that the students had difficulty distinguishing between system components and observable quantities. In order to address these issues, the concept of system and observables were refined further: observables are quantities that have units, while system components do not. Also, it was agreed that a new system example would be provided every week where the students would be asked to identify systems and observables, followed by a brief in-class discussion as to the reasoning behind the classification.

The first example was improving the efficiency of a power plant. The students were asked to identify four important system components and three observables. Many students had listed "air flow" as part of the components of the system and a discussion ensued as to whether it would be part of the system or an observable. Some students pointed out that the "air" would be part of the system. Students agreed that "air flow rate" would be part of the observables.

In the following week, faculty members on a RAT asked students identify "a principal difference between system components and observables". Almost all the students answered that observables had units while system components did not. In the same class the students were given the following task: Determine when to shut off an inlet valve of a tank into which water is flowing. For the task, students, in four-person teams, were asked to identify three system components and four observables. None of the teams had any confusion between "system components" and "observables" and a lively discussion ensued as to why the water pressure in the valve (which was properly identified by the students as an observable) was not listed in the answer provided by the instructor.

VIGNETTE NO. 6: COOLING A CANDY BAR

Warm candy bars are messy to eat, but how long does it take for a warm candy bar to be cooled to a temperature at which it can be eaten without making a mess? To address this question, the following scenario was posed to the students.

> A candy bar company wants a sheet of summertime tips for their customers. One tip addresses how long it takes to chill one of their candy bars when placed in direct contact with a chilled canned beverage.

Students were asked to identify the system components and observables. Next, students constructed a test stand using their Lego Mindstorm™ kit that will bring a soda can and candy bar in contact and maintain contact during the test. After constructing the test apparatus, students developed a Robolab [11] program for the Mindstorm™ RCS Controller brick to collect data through a thermocouple that is a part of the Mindstorm™ kit.

After acquiring the data, students plotted the rate at which the temperature changed versus the temperature. With the plot, students then explored Newton's Law of Cooling. If data points were taken every second and rate of temperature change was computed using adjacent points, the rate data was too noisy to apply Newton's Law. If the rate was computed using points that were about five seconds apart, then the plot clearly revealed a straight line. Students then estimated the slope of the straight line. Faculty members then showed how the first-order differential equation implied by Newton's Law could be solved using methods students had seen in calculus to yield an exponential function. With the exponential function and the estimated slope, students could predict how long it would take for the candy bar to reach a temperature at which it could be eaten neatly.

The candy bar project was offered in parallel with a physics laboratory experiment in which students took data on the decay of voltage across a capacitor in a RC circuit. Students were asked to describe relationships between the cooling candy bar and the RC circuit. Student responses showed that students had a very difficult time in relating the RC circuit to heat transfer from candy bar to pop can. Further, student responses to the project showed that some had trouble grasping the concept of modeling, as opposed to design. Some students saw how differential equations could be used to model a physical system. Others had trouble seeing the value of the project and what they should be learning. It appears that modeling heat transfer problems in which heat flow cannot be observed directly poses a bigger, more abstract challenge to the students than modeling forces and motion that was the subject of the next project, which will be described in a future paper.

VIGNETTE NO. 7: FIRST-YEAR STUDENT NEEDS ASSESSMENT

The Engineering Academic Programs Office (EAPO) in the Dwight Look College of Engineering conducted a needs assessment of all first-year engineering students, peer teachers, and first-year instructors in engineering, mathematics, and physics. There were several purposes for conducting this assessment. First, the EAPO is piloting a summer program to bridge the gap between high school and college to prepare incoming first-year engineering students. This survey will help identify needs of incoming students to assess students' high school preparation for college and revise first-year engineering curricula. Second, input and perceptions from students were gathered to assist with the preparation of additional instructors as the STEP curriculum becomes integrated across the college. Third, the EAPO is interested in developing methods to assist students with

learning; therefore, this survey addressed this area. Fourth, this survey posed questions about deficiencies in skills as students begin their college courses. This information is helpful in planning curriculum for future courses.

Eight weeks into the semester, after initial shocks of the first few weeks of classes and college life and before drop deadlines, students were surveyed about needs and weaknesses. Results from the survey showed that students, on average, have attended high schools with approximately 500 students in the graduating class. Most students had completed at least calculus in high school and felt mostly prepared for mathematics as entering freshman. However, when asked what specific content areas they had the most trouble with in engineering, mathematics, and physics, students overwhelmingly identified trigonometry and vectors as causes for concern. Even students who had indicated that they felt very prepared for mathematics at the beginning of the semester realized their deficiencies in these areas. Finally, many students reported that the fast pace of the mathematics course caught them off-guard.

Based upon feedback from students and instructors, it is the gap between high school and college where students find they have a lack of preparation and experience the most frustration. Initial lack of preparation eventually causes many students to fall behind in coursework and subsequently leave engineering. Some factors in the preparation gap include general issues such as time management and unrealistic expectations. Other factors include engineering-specific issues such as lack of preparation in trigonometry, vectors, and algebra. Although students did not often mention lack of preparation in algebra, mathematics, engineering, and physics faculty members almost universally cited lack of preparation in algebra. In fact, differences in perception of preparation in algebra between students and faculty members may be another important issue in the preparation gap. Students may think their algebra skills are adequate and may not invest time and energy to improve their algebra skills, while faculty members perceive that strengthening their algebra skills is critical to increasing the likelihood of success in the first-year engineering curricula. Knowing these specific issues will help the EAPO in developing the summer bridge curriculum and freshman instructors in preparing their students.

VIGNETTE NO. 8: STUDENT PERCEPTIONS

Students who complete the first engineering course ENGR 111 in the fall semester would normally continue onto ENGR 112 in the spring semester and it would normally not matter which section of ENGR 112 they selected. With the implementation of the prototype STEP program, the expectation would be that students who enrolled in ENGR 111 STEP would normally enroll in ENGR 112 STEP, and students who enrolled in ENGR 111 non-STEP would normally enroll in ENGR 112 non-STEP; however, there is no mechanism in the registration system to make this happen automatically. Further, students who participated in ENGR 111 STEP might want to continue in ENGR 112 non-STEP. To allow students in ENGR 111 STEP to have first choice for enrolling in ENGR 112 STEP, students in ENGR 111 STEP completed a form regarding their preference for continuing in ENGR 112. Faculty members teaching ENGR 111 STEP were gratified to learn that 97% of the students in their two sections wanted to continue in ENGR 112 STEP.

DISCUSSION

The first two vignettes showed activities intended to help students understand the engineering design process. As students worked on the activities, they became more aware of the need for models. They realized that models were required to help them predict the performance of their proposed designs. Faculty members also recognized that students, from their comments on end of class minute papers, understood less about modeling processes than they did about the engineering design process. Therefore, the faculty members developed problems for the second semester first-year engineering course that emphasized construction of models to support the engineering design process. Vignettes 3–6 emphasized the modeling process. Inspiration for many of the activities used within the modeling projects was offered by Starfield, Smith and Bleloch [14].

The scope of each project was kept to a manageable size to emphasize key mathematics and physics elements or engineering process issues. Complex projects that have many elements can tend to distract students, especially first-year students, from intended outcomes. In addition, with several smaller projects instead of a single semester-long project, students can return multiple times to exploration of elements in the engineering design process and/or concepts that connect the projects to physics and mathematics courses. For example, if student teams had trouble learning to manage their time and team interactions in the first project, reflection at the end of the first project and plans to improve performance for upcoming projects may help these teams to manage their time better and learn to work more effectively as a team. Also, reflection at the end of the semester can provide opportunities to synthesize experiences across multiple projects. Designed repetition is likely to improve learning of the outcomes emphasized across multiple projects. Finally, multiple projects provide a broader base of experience and allow students to work on projects that are related to several different, subsequent engineering courses. This feature is important for first-year engineering courses that are taken by students from several different majors.

Limiting the scope of some projects may reduce the challenge for some more advanced students, but observations of students who are ahead of the class indicate

that they make use of their time by taking the analysis to the next level. As an example, during the candy bar cooling exercise, students built rigs that not only held the candy bar firmly in contact with the can but also rotated the can.

ASSESSMENT AND EVALUATION

The assessment and evaluation plan for this program has been developed to support the achievement of the project outcomes. The assessment and evaluation specialist for the program participates in management team meetings in order to ensure unexpected circumstances and ongoing changes in program implementation are considered in assessing students and evaluating the program. In Fall 2004, there were seven hundred-person sections of the Track A first-year engineering courses. Two of the six sections (about 200 students) employed the innovative approach described above and were referred to as STEP (treatment) sections. Four of the six sections (about 400 students) retained the traditional first-year engineering curriculum and were referred to as comparison sections. Students enrolled in their freshman engineering courses without knowing whether their section was a STEP (treatment) or non-STEP (comparison) section.

To determine whether STEP improves first-year retention, retention of STEP and non-STEP students will be tracked. For example, fall-to-spring retention in the first year was 93% for first-time freshmen (FTF) in the STEP program and 94% for FTF in the non-step program. One-year retention percentages are expected to be smaller and may reveal differences between STEP and non-STEP groups. Although improved retention is a critical goal of the project, engineering faculty insist that improved retention cannot be achieved through lower standards. To the contrary, they are very interested in whether students are improving their understanding of mathematics, physics, and engineering and whether they are better prepared for their sophomore engineering courses.

Probably most important element of the assessment process for both understanding the impact of the STEP program and for influencing attitudes of engineering faculty regarding widespread adoption of the STEP program will be the performance of STEP program students in ENGR 221, a sophomore Statics and Dynamics course. Hence, performance data on the ENGR 221 examinations will be acquired for both STEP and non-STEP students, along with ENGR 221 faculty and student perceptions of student preparation for learning the concepts and skills of that course and other upper division engineering courses. These results will be presented in future presentations and papers.

CONCLUSIONS

A prototype of a problem-based first-year engineering course has been offered to about 200 students at TAMU. Preliminary responses from students are promising, but more complete evaluation of the prototype waits on more data.

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