A Project-based Approach for First-year Engineering Courses

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Abstract

The STEP project at Texas A&M University is working to improve learning and retention for first-year engineering students through coordinated renewal of required physics, engineering, and mathematics courses in the first-year engineering curriculum. Renewal of the two first-year engineering courses around a series of projects is the centerpiece of the STEP project. The paper reviews the challenges to be addressed by the curriculum and the needs, functional requirements, and rationales that have been developed for the engineering projects for the first-year engineering courses. Then, the paper focuses on the last of the projects that have been developed. Finally, a summary of the assessment data acquired to date is offered to help readers understand the performance of the students in the renewed curriculum.

Introduction

First-year engineering curricula have been identified as significant opportunities to improve four-year engineering 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 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.

Challenge 1. Despite the innovations introduced during TAMU's participation in the Foundation Coalition[1], retention of engineering students after one year still requires significant improvement[2-6].

Challenge 2. Engineering students require clearer understanding of the value and relevance of science and mathematics. Statements made by engineering students at University of California Berkeley are typical of statements by engineering students about 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
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> *"The problems in math have absolutely no significance at all. It's purely an exercise."*[7]

Challenge 3. Engineering faculty at larger institutions, such as TAMU, generally lack knowledge of the first-year student experiences and content of 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 the faculty members.

Challenge 4. 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 the National Science Foundation Science, Technology, Engineering, and Mathematics (STEM) Talent Expansion Program (STEP), intended to address these four challenges as it revised first-year engineering curricula.

Needs Analysis and Functional Requirements for First-year Engineering Projects

To address these challenges faculty members have developed a problem-based curricula for the first-year engineering courses. In addition to the problem-based format, the project team thought it was important to develop specifications for projects that might be implemented. Once specifications for the projects are agreed upon, the process of developing new projects becomes much easier. Lowering barriers to new project development hopefully will encourage more faculty members to participate in the development. To date, the team has identified six specific needs, functional requirements that address each need, and rationales for both the needs and the functional requirements.

- **Need #1**: Show how mathematics and physics are used in engineering
  - *Functional Requirement: Project anchors concepts of physics and mathematics to a specific engineering task*
  - *Rationale: Students must be able to use the concepts and procedures 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. Also, it should increase their ability 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. Each project anchors learning of specific physics and mathematics concepts to specific engineering tasks.*
- **Need #2**: Students connect project to their aspirations
  - *Functional Requirement: Societally relevant project*
  - *Rationale: Each project should address (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. 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. Furthermore, to the extent that projects reflect real-life applications, students are able to arrive at reasonable design specifications by themselves, and they can appreciate constraints integral to the project.*

- **Need #3**: Connect ENGR 11X to follow-on engineering classes for students and faculty
  - *Functional Requirement: Must be relevant to specific follow-on classes*
  - *Rationale: Each project should promote learning in such a way that engineering faculty members can see connections between first-year engineering projects and their 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. Emphasis on connections between first-year engineering projects and subsequent engineering courses in the sophomore or junior years is promoting greater faculty support for efforts to renew the first-year engineering courses. One of the most important lessons that EAPO learned from the Foundation Coalition was the importance of faculty involvement and support. Building connections between the sophomore and junior engineering courses and the first-year projects has been a valuable mechanism in soliciting involvement and building support. Engineering faculty who have not been involved in the STEP project have stepped forward and provided at least one additional project for consideration.*
- **Need #4**: Introduce students to notion of prediction and reasoning, not trial and error, as the basis for engineering
  - *Functional Requirement: Involves prediction and verification*
  - *Rationale: 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 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 then measure its performance. Furthermore, measuring performance and seeing that the measured performance is close to the predicted performance should increase the confidence of the students in their abilities to use science and mathematics to analyze proposed designs. It should also improve student perceptions of the value of mathematics and science in engineering design and modeling processes.*
- **Need #5**: The projects should not depend upon fabrication capabilities and should be done within the class
  - *Functional Requirement: Use prefabricated parts*
  - *Rationale: Artifacts that students assemble from non-precision components require careful fabrication techniques. Poor assembly of an artifact makes analysis difficult or impossible. Testing of these artifacts lends themselves to a more qualitative analysis as opposed to quantitative analysis. Moreover, the students cannot try out alternative designs since manual fabrication, e.g., building a truss with wood sticks and glue joints, is very time consuming. On the other hand, building artifacts from existing precision components simplifies analysis and facilitates rapid prototyping. The value of precision components has been demonstrated repeatedly in the projects that have been developed to date.*

Srinivasa et al. provide a detailed example of this rationale for the need for prefabricated parts instead of wooden sticks and glue for building a truss[8].

- **Need #6**: Students must be able to complete the project in the 2 hour/week time period
    - *Functional Requirement: Content within the course requirements of mathematics, physics, and engineering*
    - *Rationale: Although it is obvious, the existing engineering courses present constraints on available classroom time and time that students can commit to the projects. Projects should respect both these time constraints as well as resource constraints, such as classroom and lab space, that emerge from institutional support for the engineering courses*

Based on these functional requirements, engineering faculty members in the STEP program team developed five projects that address these requirements.

- **Project No. 1:** Design and predict the load carrying capacity of a truss bridge
- **Project No. 2:** Design a wheelchair lift mechanism
- **Project No. 3:** Find out how much it would cost to fix Ross Street
- **Project No. 4:** Estimate the time required to cool a warm candy bar
- **Project No. 5:** Estimate most dangerous vibrational frequency for a building in an earthquake

A thorough description of the first project in which students constructed a truss, predicted the maximum load that the truss would support, and compared their prediction with the value measured in class was described[8]. Shorter descriptions of projects 2–4 may be found[9-11]. The last project will be described in the following section.

Project: Modeling the Resonant Frequency of a Building

Tall buildings have a tendency to sway, and earthquakes tend to make the swaying motion more pronounced. Although first-year students recognize this, the challenge of how to construct a model that would allow the significant feature of the situation to be analyzed could be intimidating. The STEP project team thought this was a situation through which students could begin to refine their concept of the engineering modeling process. Modeling had been the theme of the entire second semester engineering course in the first year with the emphasis on identifying the system to be modeled in terms of parameters and variables. Earlier students had worked on the Ross Street and candy bar projects listed above. Modeling a building in an earthquake would be the culmination of their work on modeling. To help students create a model, the students were asked a series of questions intended to lead them through a process of how to construct a model in which a swaying building would be represented by the same equation that is used to model a mass-spring system.

Steps in the modeling process:

- **Create a schematic representation.** A schematic representation assembles a set of ideal elements in a configuration that represents essential elements of the situation to be addressed. What are the elements with which a schematic representation can be created? In this case, the allowed elements are mass less rods, springs whose unstretched length is greater than zero, and point masses. Mass less rods and point masses were selected as allowed elements because modeling mass distributed along the length of a rod would require greater mathematical and physical sophistication than could be expected of first-year students. Ideal springs whose non-stretched length is greater than zero were selected to reflect the fact that physical springs have a non-zero length when they are not stretched. Accounting for the non-zero, unstretched length of a spring proved challenging for students when they were constructing the equations from the schematic. Student teams were asked to draw their schematics and submit them for a homework assignment. Asking students to create a schematic involved them as early as possible in the modeling process. Then, students would be constructing their mathematical model from the schematic that they had created instead of following the faculty member through his derivation of the mathematical model he had developed. Students would then become more familiar with the overall modeling process of items that would need to be considered in the development of the schematic. Although almost every schematic had a vertical mass less rod with a point mass at the upper end of the rod, drawings of the schematic showed variety in the placement and orientations of the springs. In almost every case, each schematic a team constructed could be used as the basis for building a useful mathematical model.

- **Create a mathematical model.** Students constructed a mathematical model from the schematic through application of Newton's second law and a set of kinematic constraints. To simplify the model obtained students were introduced to the idea of a small-angle approximation for the angle between the mass less rod and vertical along with the springs rotating through a small angle. With the small-angle approximation, student teams obtained a mathematical model of the following form:

$$\ddot{\theta} + K\theta = forcingfunction$$

  where the constant K depended on the physical parameters of the schematic: lengths, mass, and spring stiffness. If the schematic had multiple springs and students had determined that the springs had different spring constants, they could replace the different spring constants with one spring constant. Students had to measure the spring constant(s) of the springs being used in two different ways to improve their accuracy in measuring the spring constant. Even though these are first-year engineering students and the model is a second-order differential equation, engineering faculty could draw on the student knowledge from the co-requisite calculus course to show how they could solve the second-order differential equation. If the project is used in the next year (2005-06), the mathematics instructor has agreed to introduce solution to second-order differential equations so engineering faculty can build on their knowledge. With the differential equation and using a zero forcing function, students could predict the resonant frequency of their model of the building.
- **Construct an embodiment of the schematic**. Students used their Lego Mindstorm™ kits to construct an embodiment of their schematics. Three variants of the models that the students built are shown in Figure 1. This step allows students to obtain hands-on experience of translating their schematic into physical reality. The students, with the model in hand and the resulting expression of the natural frequency, could then determine the best location for the attachment of the springs and masses so a target natural frequency could be obtained. An obstacle with which many students struggle is not looking at the expression for the natural frequency as a jumble of symbols but rather an expression that indicates how the system can change when one parameter is modified.
- **Verify model results.** Then, students constructed an apparatus with which they could observe the resonant frequency of their embodiment. Student teams created a rolling platform that was driven by a Mindstorm kit motor through a slider crank mechanism. The intention of the rolling platform was to oscillate the platform at a specified frequency. Students could then increment the drive speed of the motor through a

range which they had predicted would contain the resonant frequency of their structure. By observing the response of their model of the building, students could estimate the resonant frequency of their structure and compare the measured value with the predicted resonant, or natural, frequency.

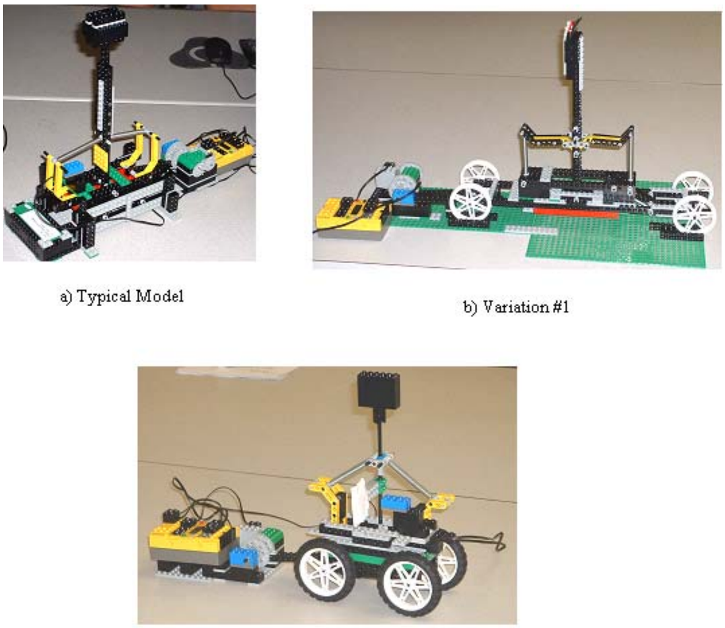
Student Responses

In order to understand how students responded to the project and what they learned as well as solicit suggestions for improving the project, students were asked to provide feedback on three questions: What did you learn from the project? What were the strengths of the project? What improvements would you suggest? Their responses are summarized in Table 1. One hundred and forty-seven students responded and categories of response that received six or more comments are provided in Table 1.

Table 1. Student Responses to the Building in an Earthquake Project

	Categories of Student Responses	Number of Student Responses in a Given Category
Strengths	Resonance, resonant/natural frequency of a building	36
	Experience in solving and/or applying second-order ordinary differential equations	33
	Experience with the modeling process, constructing a simple model for a complex system	32
	Real world application (buildings), connection with their major	29
	Robolab programming	8
	Free body diagrams	7
Weaknesses	Organization, rushed, clarity	35
	2nd Order ODE	28
	Mathematics, not yet covered	16
	Robolab programming	6

Students learned about resonance and the resonant or natural frequency of a structure (in this case, a building). They gained experience in solving and applying second-order ordinary differential equations (ODEs), and they gained experience with the modeling process. Several students commented on the value of constructing a simple model for a complex system. Many appreciated seeing a real-world application and/or connections with their chosen major. Fewer students commented on the value of Robolab programming (the language in which the RCX programming block in the Lego Mindstorm kit was programming) and free body diagrams. The major improvement that students would make to the project was its organization. Many students suggested improvements in the clarity of the project goals and requirements and many thought the project was rushed and more time should have been allowed for the project. Topically, many students wanted better background in understanding and solving the second order ODE. Many indicated that they were still confused about how to derive the solution for the differential equation and many were concerned second-order ODEs had not been covered in mathematics by the time they were working on the project. The engineering, mathematics, and physics faculty members who are working on the STEP project will work hard to coordinate topics and clarify the instructional materials. Other students, while they did not comment on differential equations, indicated that they would have appreciated a better understanding of the mathematics involved in the project. Lastly, some students indicated they would like more and clearer instruction on Robolab programming that was involved in the project. The building in an earthquake project was offered in the spring semester and about forty percent of the students in the spring semester STEP sections of ENGR 112 did not participate in the fall semester STEP sections of ENGR 111. Instruction in and experience Robolab programming was offered in the STEP sections of ENGR 111. While instruction on Robolab programming was also offered in the spring semester some of the students who mentioned more and clearer instruction on Robolab programming may have been students who did not participate in the STEP sections of ENGR 111. Transitions from non-STEP sections in the fall semester to STEP sections in the spring semester are issues to be addressed in the 2005-06 academic year.



a) Typical Model

b) Variation #1

c) Variation #1

Figure 1. Examples of the Earthquake Building Models with Rolling Platforms

Only a few students mentioned learning the small-angle approximation as a valuable result of the project; however, it is worthwhile mentioning that faculty members were reminded of the need to continue to emphasize reasonableness of computed results in connection with the small-angle approximation. On a test, students were given a problem related to the earthquake building project in which the rod was deflected two degrees from vertical. Although students did not have to use the small-angle approximation, since they could use their calculators to compute the required quantities, some chose to do so. However, some students did not remember that units were important and wrote that sin(2) = 2. When the approximation was marked incorrect, some complained that they were not told the small-angle approximation required the argument in degrees. This fact was pointed out in class; moreover, students were asked “When is the sine of an angle larger than 1?” Activities to stress degrees and radians as well as to emphasize the importance of checking reasonableness of computed results will be included if and when the project is offered in the 2005-06 academic year.

Assessment and Evaluation Plan

The STEP project is being implemented to improve retention of engineering students and learning as measured by improvements on examination scores in their core sophomore engineering courses. It is too early to provide data related to either one of these anticipated outcomes. First-year retention cannot be determined until students return and participate in fall semester courses. Data for first-year retention will not be available until the 20th class day in the fall semester, approximately October 2005. Performance in core sophomore engineering courses will be determined once students have completed those courses. Although anticipated outcomes cannot yet be determined, results to date show that students who have completed the radically different first-year engineering courses have shown retention and learning performance at least comparable to the comparison group.

To demonstrate implementation of the assessment and evaluation plan described in previous publications[9–11], results of the performance of the students enrolled in the STEP program will be compared to a comparison group. The students in the STEP program are the 180 students who were enrolled in the Track A STEP version of ENGR 111 at the beginning of the fall semester of the 2004-05 academic year. There are three tracks in the first-year engineering courses, depending on the major selected by the students. Track A is for aerospace, civil, industrial, and mechanical engineering. Track B is for computer and electrical engineering; while Track C is for biomedical, chemical, petroleum, nuclear, and ocean engineering. Since all of the STEP students had indicated a major in Track A, the comparison group of students is all non-honors students who had enrolled in a non-STEP version of ENGR 111 for Track A majors. Demographics for the two groups are shown in Table 2 below.

Table 2. Demographic Data for STEP and non-STEP Student Groups

Both Groups Exclude Honors	Fall Semester 2004-05	
	STEP	**Non-STEP**
N (number of students)	180	318
% First Time Freshmen	97.8%	85.2%
% Transfers	0.6%	13.2%
% Women	13.3%	17.0%
% Minorities	11.7%	11.01%
Mean Age	18.54	18.76
Mean SAT	1251.95	1258.95

Demographic data between the two groups is comparable, with the exception that the non-STEP group has a higher percentage of transfer students.

Table 3 shows a comparison of the percentage retained of the two groups between fall and spring semester. Table 3 shows that 157 students of the 180 STEP students continued to be enrolled in engineering in the spring semester (87.2%), while 271 of the 318 non-STEP students continued enrollment in engineering. Table 3 also provides retention data from the 2003-04 academic year, so retention data from the 2004-05 academic year can be compared to the previous academic year. Retention in the 2004-05 academic year of both groups is comparable to the retention of all engineering majors and Track A engineering majors in the 2003-04 academic year. In addition, Table 3 shows the one-year retention of the Track A engineering students in the 2003-04 academic year was approximately 20 percentage points lower than the fall-to-spring retention. Increasing the one-year retention is an anticipated outcome of the STEP prototype.

Table 3. Comparison of Fall-to-Spring Retention of STEP and non-STEP Students

	STEP N=180	**N-STEP N=318**
All Track A ENGR 111 Students Without Honors (N=498)	87.2%	85.2%
All Engineering Students in the 2003-04 academic year (806 of 947)	85.5%	
All Track A Engineering Students in the 2003-04 Academic Year (418 of 485)	86.2%	
Fall-to-Fall (one year) Retention of the Track A Engineering Students (322 or 485)	66.4%	

Another measure of the success is completing courses on the schedule documented in the undergraduate catalog. For the purposes of this paper, progression is defined as completing courses according to the catalog. Table 4 shows the data on STEP and non-STEP students with respect to progression according to the catalog.

Table 4. Comparison of Progression of STEP and non-STEP Students in the 2004-05 Academic Year

	STEP N=180	**N-STEP N=318**
Percentage engineering students enrolled in ENGR 112, MATH 152 & PHYS 208 in Spring Semester 2004-05	90/180 (50.0%)	86/318 (27.0%)
Percentage students enrolled in ENGR 112 and meeting remaining Math & Physics requirements of first year engineering program	1/180 (0.6%)	47/318 (14.8%)

Percentage all students in Track A ENGR 111 who progressed or satisfied required first-year engineering courses in Spring 2004-05	91/180 (50.6%)	133/318 (41.8%)

The first line shows the percentage of students who were on track based on completion of and enrollment in the courses specified in the catalog. However, some students have completed course requirements by satisfying advanced placement (AP) requirements or taking one or more courses at another school before transferring to TAMU. The percentage of students who met catalog requirements using one of these additional mechanisms is shown on the second line. Summing the number of students in the first two rows yields the percentage of students who are on track. These percentages are shown in the third row. Note the percentage of STEP students who are on track is 50.6% while the percentage of non-STEP students who are on track is 41.8%. Progression will continue to be tracked to determine any differences between the two groups. For comparison purposes, Table 5 shows the progression data for the Track A students in the 2003-04 academic year.

Table 5. Progression of Track A Engineering Students in the 2003-04 Academic Year

All groups include students with Track-A majors who took ENGR 111 in fall, excluding Honors classes	**N=485**
Percentage engineering students enrolled in ENGR 112, MATH 152 & PHYS 208 in Spring Semester 2003-04	173/485 (35.7%)
Percentage students enrolled in ENGR 112 and meeting remaining Math & Physics requirements of first year engineering program by Spring 2004	31/485 (6.3%)
TOTAL: Percentage all students in Track A Majors of ENGR 111 who progressed, or satisfied first-year engineering required courses in Spring 2004	204/485 (42%)

Here the entering number of students is 485. The 2003-04 progression data are comparable to the data for the non-STEP students.

Students are not always successful the first time they take one or more of the required mathematics, engineering, or science courses. However, many of these students can be valuable engineering graduates if they succeed when they retake courses they did not successfully complete the first time. Therefore, one element related to increased retention is how well students who retake required courses perform. Data from the 2004-05 academic year on students who repeat physics and mathematics courses are shown in Table 6.

Table 6. Performance of STEP and non-STEP Students who Repeat MATH 151 Calculus I and PHYS 218 Mechanics Courses in Spring Semester 2004-05

	STEP Mean GPA (Number retaking/Potential	**N-STEP Mean GPA (N) (Number retaking/Potential**

	retaking)	**retaking)**
MATH 151 Calculus I	2.33 (34/52)	2.15 (29/47)
PHYS 218 Mechanics	2.82 (18/36)	1.93 (14/29)

As shown in Table 5, STEP students who repeated either MATH 151 and/or PHYS 218 had a higher average GPA than the non-STEP students. In the case of PHYS 218, the difference is one letter grade. Improved performance of students who retake required courses is a potential indicator of improved retention. Table 6 also shows the number of students who retook MATH 151 or PHYS 218 compared to the number of students who did not successfully complete the course the first time. For the STEP students taking MATH 151, there were 52 students who did not successfully complete the course the first time, and 34 students retook the course. If the percentages of students who retook the course with respect to the number of students who might have retaken the course are compared, then the percentages for the STEP and non-STEP students are virtually identical.

The STEP project team has analyzed in detail differences in performances in the four required mathematics and physics courses: MATH 151, MATH 152, PHYS 218, and PHYS 208. Based on analysis of common examination scores (where available) and grades in the four courses, no significant differences between the performances of the STEP and non-STEP students was found. Grades in the two first-year engineering courses ENGR 111 and ENGR 112 have been examined, but since the grades in these two courses are typically higher than the grades in the mathematics and physics courses, more detailed analysis of the grades in the latter courses was performed.

Conclusions

Faculty response in civil and mechanical engineering to the functional requirements that have been generated for the projects and the specific projects developed to date has been very positive. Two new faculty members are working on projects for the 2005-06 academic year when 500 students are scheduled to enter the STEP version of the first-year engineering curricula. Preliminary data suggests that the radically different project-based engineering courses have been successfully implemented. The real test is when the first-year engineering students return for their sophomore courses. Then, retention and learning from the first-year courses can be more accurately gauged.

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