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Engineering Students for the 21st Century: An ongoing case study in curriculum reform at a large state university

Introduction

This paper presents a case study of *Engineering Students for the 21st Century* (**ES21C**), an ongoing effort to reform the undergraduate electrical engineering program at Oklahoma State University (**OSU**). OSU is a large, research intensive, land grant institution with approximately 20,000 students. The School of Electrical and Computer Engineering (**ECEN**) enrolls approximately 400 undergraduate students, primarily Oklahoma residents. The engineering program is similar to programs at peer institutions, with a two year pre-engineering curriculum followed by a two years of discipline-specific courses. Most students take five years to graduate, and the graduation rates of students entering the program as well as student diversity are below national averages. The faculty teaching load is higher than that at many peer universities, and reward and promotion is tied closely to research. Before the reform effort reported here, there had been no major changes to the electrical engineering curriculum in over a decade.

This paper is organized chronologically. The first section reports on the initial reform effort using a trial model that involved five courses that replaced lecture with case studies[1,2], problem based learning[3], and a modified form of team learning[4,5]. The second section of this paper discusses how ECEN is beginning implementation of more comprehensive reform to emphasize student development. The comprehensive reform, funded through a National Science Foundation Department Level Reform Implementation award, avoids many of the pitfalls and errors made in the initial reform effort.

Preliminary Curriculum Reform Efforts

In late 2002 curriculum reevaluation was started through support of a National Science Foundation Planning Grant for Department Level Reform of Engineering Education. The reform effort was based on the hypothesis that learning was enhanced when engineering courses were relevant to students' existing preconceptions of engineering, and students' experiences in the classroom match their preconceptions. Relevance was created by focusing reform around three goals. First, student engagement and attitude would be improved by changing courses from a traditional lecture format to one which emphasized in-depth analysis of authentic problems by student teams. Reformed courses sacrificed breadth of coverage for depth of understanding. The second goal was to make students more independent learners who relied less on the instructor for understanding and more on peers, books, or computer models. Courses reduced the emphasis on summative evaluation, and replaced it with formative evaluation. The third goal was to provide experiences that mimic the environment of practicing engineers by incorporating team projects emphasizing communication and peer evaluation.

Five courses were chosen based on the willingness of faculty to participate. The courses impacted were two undergraduate photonics electives that had been using the model for two years, introductory lecture courses in digital logic design and electromagnetics required for all electrical engineers, and the introductory engineering economics course required for all engineering students. Other participants included a faculty member from the OSU library and a colleague in education. A total of eight faculty participated.

During the first semester, faculty learned the teaching techniques used in the project: case studies, team learning, and project-based learning. Biweekly meetings let faculty discuss problems and concerns they felt in transitioning away from lecture. Faculty beliefs about teaching were deeply rooted in personal experience, some of which were compatible with the assumptions inherent to this project and others that were not. The major, unanticipated problem encountered in the preliminary reform effort was how difficult faculty found changing personal beliefs about teaching.

In the second semester, faculty taught each course as a "control" using lecture; the exceptions were the photonics courses which had previously transitioned. During the summer semester, faculty, in conjunction with students supported through an REU supplement, transitioned courses to the ES21C model by developing case studies, formative evaluation tools, and in-depth projects. Three courses were taught using the ES21C model in the fall semester. Each faculty member modified the model to address specific course outcomes and better conform to their personal beliefs about what constituted effective teaching[7]. Despite differences, three basic elements were consistent in each of the reformed courses: (1) knowledge was organized around a relevant problem, (2) students mastered relevant concepts both individually and in teams, and (3) student work was focused on realistic deliverables.

To evaluate the effect of the trial curriculum reform, faculty were surveyed about perceived gains or losses in their students as well as the relative increase in workload. The six teaching faculty were also asked to compare the reformed courses to the lecture courses on multiple outcomes organized around four major themes. A Likert scale was used to quantify faculty responses (1 = great loss, 3 = neutral, 5 = great gain). Overall, faculty reported increases in all areas: student learning (mean = 3.5, $\sigma = 0.5$), the time spent in teaching and preparing for Phase I courses (mean = 3.3, $\sigma = 1.0$), the attitude and maturity of students (mean = 3.7, $\sigma = 0.4$), and whether students developed useful skills (mean = 4.0, $\sigma = 0.3$). Faculty only reported losses on the amount of curricular material that they were able to cover in the course, an expected result. The largest reported gains were in the maturity, responsibility, and initiative in students.

Faculty reported that there was a significant increase of time spent in preparation of course materials compared to lecture. The major time sinks for faculty were (in order of reported importance): developing web-based curricular materials, creating laboratory assignments, and training student teams. Faculty believed the time commitment would be reduced in further iterations of their course.

Open-ended questions on the survey reflected the individual approach faculty took in implementing reform in their courses. Several points were consistently reported by all faculty and supported by student responses (see below):

1. Faculty who explicitly addressed team building and implemented peer evaluation in their classes had fewer problems transitioning to team-based projects.
2. Faculty who had prior experience in the teaching techniques used reported more success than inexperienced faculty.
3. While all faculty reported that personality conflicts created difficulties on teams, they felt that students gained significant teamwork skills.
4. Faculty reported that the ES21C model helped motivate students, but disagreed on how uniform this increase in motivation was.
5. Faculty felt that lower performing students could "slip through" the course; learning less, but received a higher grade than they deserved.
6. Faculty better understood the diverse learning styles used by students by the end of the project.

To evaluate students, a student assessment of learning gains (SALG)[8], a "Draw an Engineer" exercise[6], and evaluation of student work (proposals and final reports) were used. Comments from the SALG allowed qualitative and quantitative comparison between classes taught before and after the course reforms. A total of 81 students completed the SALG in lecture courses and 76 in the reformed courses. Student comments were divided into four general categories: how students learned; how well students learned; attitude, motivation, and relevance; and course organization and structure, including teamwork. Overall, lecture courses showed a normal (bell curve) distribution of responses while student responses to the reformed courses were normal or bimodal. The cause of the bimodal distribution is not known, although it was consistent across courses. The response rate of students was consistently higher in reformed courses than in lecture courses. The majority of comments came from the electrical engineering courses, very few comments were made by students in the engineering economics class. Themes from student responses in each of the four broad categories are discussed below.

<u>How Students Learned:</u> Students saw lecture as a vital part of learning, but relied on lecture to "tell them what to learn". Most students reported textbooks were difficult to understand and tended to rely on lecture if it was offered. "*I did not even open the book once the whole semester, nor did I do any of the suggested homework problems, but I still feel like I know this material very well*". Three times as many comments on deficiencies of the textbook were made in the reformed courses in which students were more reliant on the book. "*I also found it difficult to learn the material strictly from the book and depend [sic] on others to help me.*" Students alluded to a belief that grades on tests and quizzes accurately measured their level of understanding. "*Did not like the format of the class at all. Should have had tests to test what we have learned instead of having a final out of the middle of nowhere.*" The most prevalent positive comments were about the design projects. Overall, student comments indicated they learn by multiple methods, but are habituated to lecture and summative evaluation and feel discomfort when these familiar feedback channels are removed.

How Well Students Learned: In two courses there were a significant number of comments on how well students learned the material. Students overwhelmingly reported they learned more by incorporating projects into courses. "*Even though this class is more work, is very demanding, can be confusing, and can be frustrating at times; I feel that I learn better by actually doing. I will definetly [sic] retain it better.*" In lecture courses students did not feel that they were able to apply the concepts or mathematics to any relevant problem. "*The ways the formulas and equations are taught seem to lack in teaching us how to find the important information to select, setup, and use some of the formulas and equations.*" Comments reflected that students in lecture courses applied a trial and error approach which broke down when the course content become unintuitive. "*Even if I knew the math and the concept it wouldn't have helped me because I didnt [sic] know how to relate them*".

Attitude/Relevance: Overall, students in reformed courses reported a more positive attitude than those in lecture courses and that these courses were more relevant. "*I think that this class is a good step in making learning what it should be -- a vibrant and enjoyable experience.*" Students reported the reformed courses were more relevant. In lecture courses students' perception of what they would be doing after graduation affected relevance, highlighting the need to make material relevant to student perceptions of what an engineer does. Students reported a high workload with the *same* frequency in lecture as in reformed courses. Student comments about faculty were overwhelmingly positive in both formats.

Organization and Teamwork: The most problematic aspects of the preliminary reform courses were how fair students perceived the grading to be. "*What is expected in the reports should be more clear."* Transitioning to a new style of teaching/learning made students uncomfortable, and faculty were not sufficiently aware of the stress that would be created on students despite reports in the literature[7,9]. Creating a secure environment for students in which their efforts are immediately rewarded is critical to this type of curriculum reform. Students also did not know how to function effectively on teams, and were not comfortable with peer or self evaluation. Despite the reported difficulties on teams, students overwhelmingly reported they were much better able to function on a team by the end of reformed courses and the experience prepared them for a career or capstone design.

To highlight changes between lecture and reformed courses we looked at differences between the extreme numeric responses SALG data (1 & 2 responses vs. 4 & 5 responses on a Likert scale) of lecture vs. reformed courses. Faculty identified ten course outcomes (from 77 SALG questions) that were associated with students who are independent learners (i.e. using the textbook, teamwork, enthusiasm) and six outcomes associated with dependent learners (i.e. learned facts and equations, got help from professor or TA). While there were gains and losses in learning outcomes in each course, the overall sum of gains and losses was positive (representing an increase) in outcomes associated with independent learners and negative (decrease) in those associated with dependent learners. The photonics courses are not represented in these pre/post results. The exception was the engineering economics course which saw decreases in both categories, but larger

decreases in outcomes associated with dependent learners. Although the overall results were skewed by the negative results in the engineering economics course, there were increases in teamwork and communication in all courses. Overall changes in student learning reported through the SALG in *all* pre/post courses are shown in Figure 1. Significant curricular change will result in gains in some areas and losses in others.

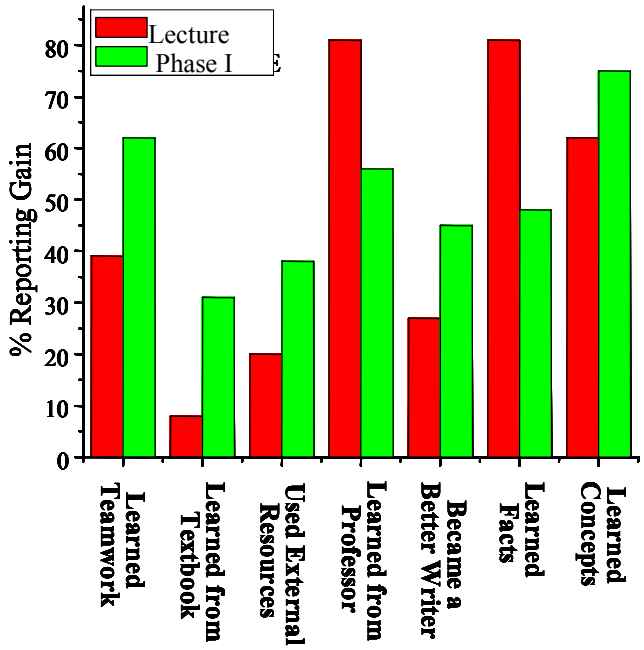

Figure 1: Reported Gains in Phase I vs. lecture courses

The photonics courses had been previously transitioned to the ES21C model at the start of this project, so that pre-post measurements were not possible. However, nearly four years of SALG data is available for these courses, as well as a wealth of individual statements drawn from student portfolios and peer evaluation data. This allows a more in-depth analysis of the effect of particular aspects of the ES21C model in a scenario where many of the "bugs" of new course implementation have been solved.

Qualitative analysis on repeated themes in personal statements taken from project reports was compared with Student Assessment of Learning Gains (SALG) responses. Simple descriptive statistics from the SALG were also measured. Over five years of data, the sample size is greater than 100 students. In these elective courses 85% of the students indicated that the present course format was better than a standard lecture format in terms of learning gains, and 94% felt that they learned more from working in a team than by themselves. Negative comments centered on one of two issues: unfair distribution of effort and language barriers. The case study had a more important role in making course material relevant to students that was originally envisioned. 94% of students indicated the case study made the presented problem relevant while 78% felt that the use of open-ended projects made the material more relevant and promoted learning. Relevance was a significantly repeated theme in the student project statements. In comparison to the responses of students in the lecture classes, students in the photonics courses are four

times more likely to consider attending graduate school. Individual statements highlight the importance of being able to engage in in-depth projects in this decision.

The Path Forward: Basing Reform on Student Development

The preliminary reform period of Engineering Students for the 21st Century in 2003 was followed by a two year period in ECEN put reform efforts on hold to prepare for (and recover from) ABET accreditation. During this time faculty refined the curriculum reform model based on positive and negative experiences in the preliminary reform project and from experiences of others engaged in reform[7,9]. The major lessons drawn from the preliminary reform that are being implemented in the second phase are:

1. Reform needs to draw on experience and guidance from outside the university. ECEN is adopting the three goals of effectiveness, engagement, and efficiency created by the Center for the Advancement of Scholarship on Engineering Education.
2. Reform needs to focus on creating a relevant context for learning rather than by focusing on content. Reforming the degree program by replacing legacy material proved not to be a valid path to curriculum reform. There is no universally accepted way to identify legacy material since it depends on the *context* in which it is taught rather than any *intrinsic merit* of the material itself.
3. Reform needs to move OSU's engineering program away from the paradigm that covering a specific set of concepts prepares students for a career in engineering. The fallacious assumption inherent in this paradigm is that specialized information can only be found and learned at universities[10].
4. Positive experiences in the initial reform effort were those which created gains in student cognitive development. Students learning gains were much greater when they were trained to monitor their own learning, function on teams, and document and reflect on their work.
5. Learning gains in problem solving and critical thinking will be balanced with losses in rote memorization and the number of facts learned. We assume that information technology will compensate for these losses and they will not negatively impact students' preparation for an engineering career.

The second phase of *Engineering Students for the 21st Century* commenced in the fall semester of 2005 and will continue for four years. Since ECEN is in the preliminary stages of this reform project the remainder of this paper discusses the model that is being implemented rather than any specific experiences or data.

Drawing from the first phase of ES21C, ECEN is transitioning a portion of the electrical engineering curriculum from a knowledge-based paradigm (acquiring a set of concepts) to being development-based (emphasizing students' development). ECEN's current, knowledge-based program is defined by a specific set of concepts students should learn. An inherent assumption is that by learning these concepts students will be able to function as engineers. In the development-based reform being implemented students are taught the *process* of solving in-depth problems in addition to the concepts needed to understand them. Concepts that are not germane to the problem are not taught; they

become legacy material in the context of the problem. To transition from being knowledge-based to development-based, a *breadth on top of depth* approach[11] is being used that combines breadth in the curriculum with depth in individual courses. This approach asserts that depth of understanding in a limited number of topics is of *equal or greater importance* than gaining a broad overview of electrical engineering. Today's students are able to access information on any subject nearly instantaneously, but need to learn how to filter and use information.

Transitioning our program to focus on student development is being accomplished through two complementary objectives, discussed below. First, ECEN will increase the depth of student learning by restructuring courses to emphasize student development. Second, to ensure reform is sustainable, ECEN is trying to actively engage both current and future faculty in the curriculum reform effort by aligning teaching with scholarship.

Emphasizing student development over knowledge acquisition

Many ECEN courses emphasize *shallow* or artificial learning, over *deep* or authentic learning. Shallow learning[12] refers to students' use of strategies like pattern matching or memorization and is reinforced by contrived test or homework problems. In contrast, authentic learning sets tasks for students that mimic those used by practicing engineers. A prerequisite for development is that students become engaged in the engineering program, which requires authenticity. To be authentic problems must be relevant to *students'* preconceptions of engineering. In other words, it is vital that *students*—not just faculty—perceive problems as authentic. The essence of reforming courses to emphasize student development is that to *become* engineers students need to continually practice *being* engineers.

To develop deep or authentic learning, the development model used in this project is based on Bloom's Taxonomy[13] that identifies six levels of learning and helps identify characteristics of students who have mastered each level. A simplified version of this model is shown in Figure 2. Levels of learning are represented by shaded boxes; the name of each level is at the left. Shallow levels of learning (i.e. remember and understand) are at the top while deep levels (evaluate and create) are at the bottom. The model is hierarchical- to reach deep levels of understanding it is necessary that students first have mastered the shallow levels. An analogy is excavating an open pit mine to reach ore deep underground. Example tasks that students might undertake to develop the skills needed to advance to deeper levels are listed to the right of the arrows. For example, once a student has remembered information, the course or instructor needs to *provide feedback* on student work to ensure they understand the material. The inverted pyramids at the right of the figure represent the relative amount of emphasis placed on each level in freshman or senior classes respectively. Early courses emphasize shallow levels of Bloom's Taxonomy, while upper division courses place more emphasis on deeper levels. All courses still cover material hierarchically, however, placing more relative emphasis on remember than understand.

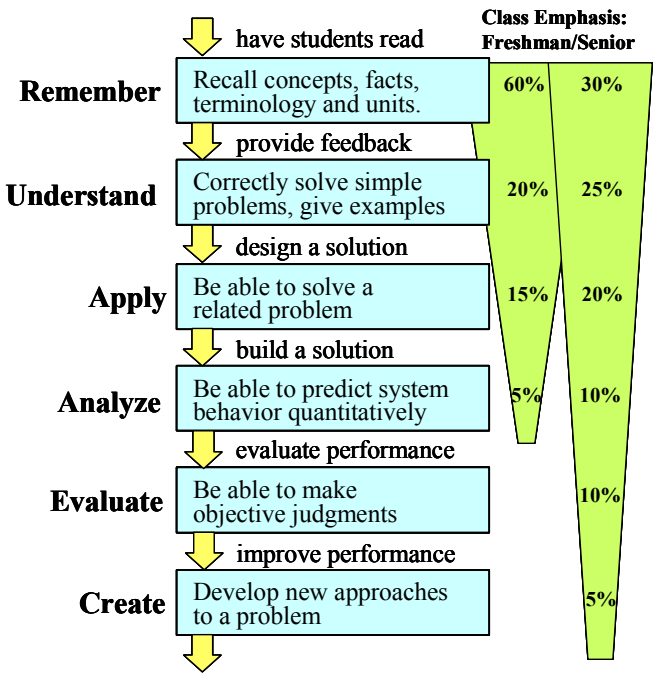

Figure 2: Bloom's Taxonomy used as a developmental model to identify and develop deep levels of thinking in students.

This developmental model is being implemented by faculty in individual courses. The preliminary reform project discussed previously emphasized that faculty need the freedom to select techniques most compatible with their own beliefs and teaching styles. However an uncoordinated set of teaching methods forces students to continually adapt to changing expectations with negative consequences to learning[14]. This is a fundamental conflict with developmentally based programs such as ES21C, particularly at research intensive universities like OSU. Students need a coherent program, while faculty need the freedom to innovate. In recognition of this conflict, reformed courses share a common structure or *strategy*. All development-based courses share this structure and organization based on six sequential steps designed to foster student development:

1) Structure learning around two or three fundamental problems rather than a fixed set of concepts.
2) Train students in the teamwork skills.
3) Pose the problems to students through a case study.
4) Walk students through the process of solving the problem posed in the case study in three steps based on Bloom's Taxonomy:
   (4a) *Remember* and *understand* concepts needed in solving the problem outside of the classroom.
   (4b) During class periods student teams *apply* what they know and *analyze* the problem under faculty guidance.
   (4c) Have student teams *create* a solution to the problem then *evaluate* how well it works.
5) Have students build an engineering portfolio.
6) Let students reflect on their understanding and experiences.

Although these six steps guide the curriculum reform *strategy*, faculty will choose techniques (*tactics*) that best suit their teaching style, course goals, and level of their students. The organization, timing, and the structure of a one semester course structured on this development model are shown in Figure 3, below.

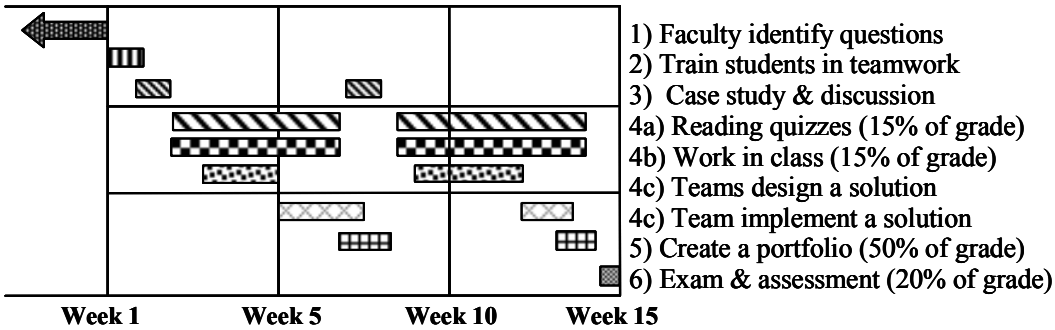

Figure 3: Organization of a class based on the developmental model that addresses two questions, technologies, or problems.

Step 1: The first step in reforming a course is for faculty to identify two or three questions, technologies, or problems that are fundamental to the course. The figure below shows how this was done in the introductory electromagnetics course in Phase I. Three projects—a resistive position sensor, a strip-line filter, and a patch antenna—were chosen that reflected three fundamental questions about electromagnetics. The concepts students needed to learn were then ordered or matched to each of these questions while the class was being developed. Concepts which are not needed to solve the problem *are not taught* since they represent legacy material in the *context* of the problem or question addressed in the class.

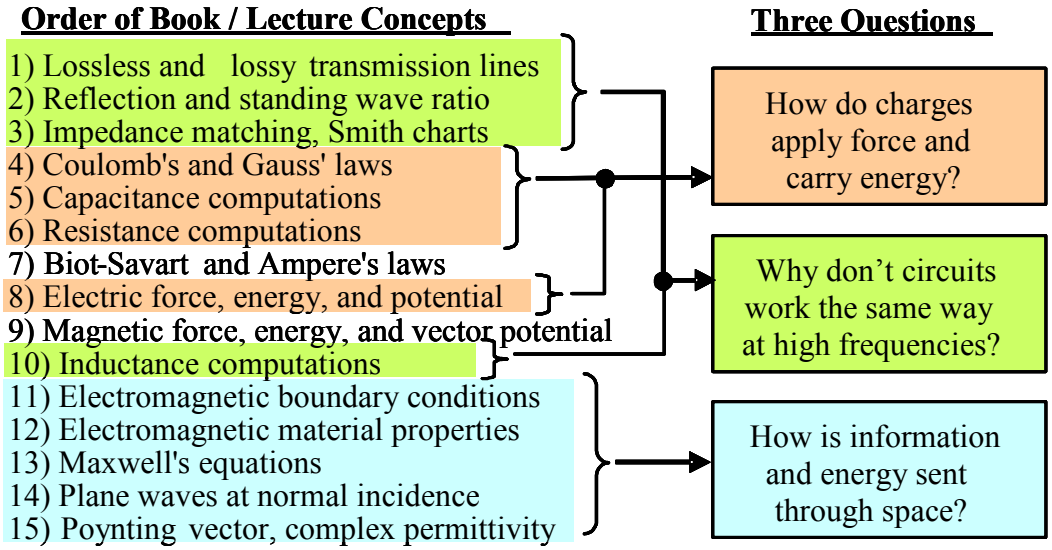

Figure 4: Example of restructuring a course to address three in-depth problems.

Step 2: The second step is to train students to function on teams so they are able to draw from the array of resources that available from the diverse individuals on a team.

Students address all deeper levels of learning (apply through create) as part of a team. Rather than forming ad-hoc groups, student teams are well-organized[15,16] and trained in effective team functioning during the initial week of the course.

Step 3: After students have been trained to work on teams, a case study[1,2] introduces the problem in a context that is relevant to students. Class discussion helps students identify what concepts they need to learn to solve the problem posed. The case study shows the relationship between technical concepts and their social and ethical impact, limitations due to resource availability, and inter-personal conflicts.

Learning the relevant concepts and their relationship to the problem is done in three steps. Each step uses different techniques depending on the level of learning (from Bloom's Taxonomy) that is being addressed.

Step 4a: Shallow levels of learning—*remember* and (for upperclassmen) *understand*—can, and should, be mastered independently. Students are given a reading assignment that covers one or two specific concepts prior to each class period. Faculty use techniques that help students learn material independently such as Just in Time Teaching[17], Team Learning[4,5], or the use of web-based, interactive quizzes[14]. Work outside of class contributes the minimum fraction of a student's grade (~15%) needed for them to apply themselves.

Step 4b: The time previously spent in lecture is used to relate the concepts the students learned outside class to the problem and make connections to concepts learned earlier. Active learning or team learning is used to **directly** address the process of solving the question posed in the case study. In other words student solve portions of the in-depth problem in class. Teams work in parallel rather than sequentially[5,16] so all students are occupied. While teams are working on the assignment, the instructor and TA's move throughout the classroom explaining how to apply concepts and immediately correcting misconceptions. These in-class exercises contribute a small fraction of a student's grade, on the order of 15%.

Step 4c: To develop skills in evaluating and creating knowledge, students apply newly learned concepts by solving the problem posed in the case study. The work in class guides the process of problem solving which is broken down sequentially into two stages, with faculty feedback after each stage. The first stage is to design a solution, either as part of the work in the classroom or in a separate design proposal[18] in which a team provides evidence the design will work[19] (i.e. computational modeling), evidence the team has an organized approach (block diagram or flowchart), and evidence students have defined roles (Gantt chart). The second stage begins when a team's proposal is accepted and they are given access to the resources needed to implement their solution. This phase of evaluating understanding may involve building a solution or characterizing the device they designed during the proposal phase. To make this experience as authentic as possible, teams choose the equipment they need from an on-line catalog common to the entire electrical engineering program, and set it up on a bare laboratory bench. The price of all equipment is listed since teams assume ownership of, and responsibility for,

the equipment and supplies they check out. Unlike traditional labs, students self-schedule times to work on the project and teams from different classes share the same room[20].

Step 5: Teams conclude the design exercise with a written report[15]. A key component of this report is a set of measured specifications to quantify the problem. Engineering students generally have difficulty creating specifications, a key element in developing critical thinking skills in engineering. The reports are worth a significant fraction (~50%) of a team's grade, and a grading rubric[19] is used. An individual student's grade on the report is scaled by a peer rating[5].

Step 6: Students conclude their investigation by reflecting on their experiences and being tested on what they learned. At the end of the course, a final examination is used to measure changes in student learning. Structured formats for examination questions are used to evaluate changes in student development during the course.

Engaging current and future faculty

One of the lessons faculty drew from the preliminary reform project was that sustainable reform requires that faculty find intrinsic interest the reform process. Building this interest is being undertaken by creating learning communities among both faculty and students[21]. Community building is being undertaken through several channels including a campus-wide, semiannual workshop on student learning and engagement, funding travel for faculty and graduate students to attend workshops, supporting faculty research in education by setting aside matching funds for competitive education proposals, and revising promotion and tenure requirements to emphasize education.

Since curriculum reform is time-consuming, ECEN is actively recruiting graduate students for a joint teaching-research program to prepare Ph.D. students for academic positions. Graduate students will be given opportunities to both teach classes and develop curricular materials in conjunction with more traditional research.

Assessment: Measuring the impact on students and the program

To assess how emphasizing student development over knowledge acquisition affects student learning, project evaluation is focused on three questions that reflect the main goals of this project: 1) what are the gains and losses in student learning, particularly at different levels of Bloom's Taxonomy; 2) how does removing the redefined "legacy" material from the curriculum impact student learning; and 3) how does using graduate students rather than faculty in undergraduate courses impact student learning?

Assessment of student learning is both formative and summative. Formative assessment guides both the instructors and the project, while summative assessment is used to evaluate long-term success. To the extent possible, assessment tools are based on coursework to minimize extraneous work on both students and faculty. These include rubric-based analysis of individual and team contributions to proposals and project reports[22,23], results of formative on-line quizzes, and final exams given in the format of a case analysis test[24]. These measures are compared to student responses on Student

Assessment of Learning Gains surveys given in each course. A more programmatic measure of student learning will be obtained from a conceptual diagnostic test built from existing instruments in electrical engineering[25] administered during the senior year.

Changes in student attitude and engagement will be measured by a version of the National Survey of Student Engagement (NSSE) being developed at the National Academy of Engineering. Student retention will be tracked throughout the project, and an alumni survey tracks students who graduate. The Motivated Strategies for Learning Questionnaire will be given in the sophomore and senior year to measure changes in metacognition.

Conclusion

One of the critical challenges for the United States is creating enough engineers to support our economy, infrastructure, and national defense; all of which rely heavily on technology. The government, National Academies, and some business leaders are acutely aware of a looming crisis in the United States' continual demand for a scientific workforce. Several national-level panels have been formed to give advice on this need, but it is still an open question about how universities can accomplish reform that it is cost effective and sustainable.

Engineering Students for the 21st Century is the response of OSU's electrical engineering program to the challenge of educating the next generation of engineers. This paper has presented a case study of this reform effort, reporting on a preliminary phase which impacted five courses, and a second phase that will affect all four years of the curriculum. The first phase allowed faculty to gain experience in a reform model built on integrating problem-based learning, case studies, and team learning. Gains and losses in student learning were measured, with gains corresponding to students becoming more independent learners.

This reform project is just beginning the second phase in which a (hopefully) sustainable model of course reform based on student development guided by Bloom's Taxonomy is being implemented across the curriculum. The reform project challenges the paradigm that covering a specific set of concepts will prepare students for a career in engineering. By emphasizing student development in the context of in-depth problems students will be taught how engineers tackle design problems, how to monitor their own development, and how to find, evaluate, and communicate information. This approach redefines the role of both faculty and the university, and represents a fundamental shift in the focus of an engineering degree.

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