A Sophomore-Level ECE Product Design Experience

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I. Introduction

Driven in part by ABET Engineering Criteria 2000, engineering educators are increasingly integrating design concepts and experiences into their curricula. The most common form of this integration is the senior capstone design experience, although many universities also introduce basic notions of engineering design in the first year. Traditional coursework alone may not adequately prepare students for rigorous senior design experiences, however, and the role of senior capstone design in the curriculum is more summative than formative, leaving little room for remediation and subsequent improvement. First-year design experiences can provide context, motivation, and excitement, but first-year students are typically without the technical background to experience a genuine electrical and computer engineering (ECE) design process that fills an unmet need and addresses all of the tradeoffs between technical and nontechnical matters that occur in product design.

For over 30 years, the undergraduate engineering programs at Worcester Polytechnic Institute (WPI) have featured a substantial senior capstone design project as one of three degree-required project experiences. While faculty reviews of the ECE design project reports consistently revealed that design content was consistent with WPI's and ABET's expectations, reviewers also noted that some considerations of the design process—for example safety, reliability, aesthetics, ethics, and social impact—were not evident from the report documentation. Similarly, not enough reports revealed appropriate use of simulation and design analysis steps, or consistently made clear how students synthesized designs from user requirements, design criteria, and technical specifications. These shortcomings were in some cases exacerbated by students' lack of experience in applying fundamental principles in the context of the design process.

The faculty concluded that a *formative* ECE design experience could address these issues. The WPI ECE Department instituted a sophomore-level course entitled "ECE Design" with the specific intent of better preparing students for their senior capstone design projects, both by reinforcing fundamental concepts and by leading the students through a formal design process with emphasis on the process itself. The course is run as a simulated business, with faculty serving as "Engineering Managers" who teach the process of design and manage the learning experience. The students are placed in 3-person design teams reporting to undergraduate "Senior Engineers", who help guide them through an open-ended design of a useful product, from market research to demonstration of a working prototype. The students are given a working budget and a target product cost, and complete an economic analysis for their product. Their work is reported out on a weekly basis to the faculty, and at the end of the course to external evaluators in formal Design Reviews.

Faculty and students both report that this intensive course has resulted in better-prepared students with a sense of pride in their accomplishments. It also serves as a valuable "checkpoint" for assuring that students understand and can apply basic material and concepts, and occurs early enough in the curriculum to allow remediation. The ECE Design course has become a *de facto* requirement for ECE students at WPI, as most faculty members require that students successfully complete the course before embarking on their senior design project. This paper will describe how and why the course was developed, how it is implemented, and what preliminary effects it has had on the curriculum and to the senior design projects. The learning outcomes associated with the course and their assessment will be discussed, as will the results of surveys reporting student behavior and attitudes with respect to the course.

II. Motivations for a Sophomore-Level Design Experience

WPI's undergraduate programs are project-based; each student must complete three significant projects to receive the bachelor's degree. One of these required projects, the *Major Qualifying Project* or MQP, takes the form of a senior design experience for engineering students. Equivalent in credit to three courses (nine credit hours), the MQP is typically done in small teams under close faculty guidance, and involves addressing an open-ended design problem. Many of these design projects are done for corporations, agencies, or other external organizations, while others are related to faculty research programs.

The MQP is an important component of students' engineering educations at WPI, and as such it is periodically subjected to learning outcomes assessment through a series of peer reviews[1] of the extensive written reports that document the process and product of each team project. During MQP reviews in the mid-1990s, the ECE Department faculty, while noting that most of the educational goals for the MQP were being met, discerned a number of areas for improvement:

- Many design projects did not appear to be framed in terms of *user requirements and technical specifications* derived from those requirements;
- Many project reports did not reveal appropriate *design synthesis*; rather, students tended to address design challenges by choosing a single likely solution and "making it work";
- Little attention was given, in many cases, to such fundamental design considerations as *cost, quality, reliability, maintainability, aesthetics, and safety.*

In addition, ECE faculty when advising MQPs had noted that with the broadening of the field of ECE came an increase in the numbers of students who entered their senior design project either without an adequately broad knowledge of the fundamentals of ECE (analog and digital circuits, signals, fields, and underlying physical principles), or without the ability to relate these fundamentals to each other and apply them in a design context. Thus, the faculty took into consideration additional concerns:

- Given the broadening nature of electrical and computer engineering, and the rapid changes that the field will experience during students' careers, it is more important yet more challenging than ever that ECE students develop a *firm foundation in the basic phenomena, principles, and concepts* underlying ECE, and *understand their interrelations and practical application*.

In response to these concerns, the course *EE 2799: ECE Design* was developed in 2000[2] by three ECE faculty who between them had over 70 years of experience as practicing engineers and engineering managers. The course has since become a *de facto* requirement for all ECE students, and is typically taken at the end of the sophomore year, by which time students have typically completed five or six ECE courses covering fundamental areas (analog and digital circuits, systems, signals, basic electronics, fields, microcontroller hardware and software). The course simultaneously serves two purposes:

(1) *to reinforce fundamental concepts and skills* from core ECE courses in context of their application, and

(2) *to teach design as a process* by focusing on product design synthesis in response to user requirements, and by emphasizing the economic, ethical, and other nontechnical issues that influence engineering design.

III. Educational Outcomes and Assessment for the Design Course

Assessment of learning outcomes plays an important role in WPI's undergraduate programs. Although many outcomes are best demonstrated through the three required projects, course-based assessment is also an important component of evaluating the program. Each first- and second-year ECE course has a set of explicit learning outcomes (typically between five and seven) that has been agreed upon by the faculty members who regularly teach the course. The progress of each student with respect to each outcome is monitored and used to evaluate and improve the courses and overall curriculum.

The list of learning outcomes for the ECE Design course is unusual in both its breadth and depth, and reflects the high expectations that are placed on the student design teams. Students passing ECE Design are expected to demonstrate:

(1) knowledge of the steps involved in the engineering design process;
(2) the ability to apply the engineering design steps to a real design problem;
(3) the ability to contribute successfully to a team effort;
(4) an understanding of the ethics, reliability, safety and regulatory issues in the design process;
(5) a working knowledge of the financial, scheduling, and other administrative elements of the design process;

(6) the ability to effectively use written communications to report project status and results; and
(7) the ability to effectively use oral communications to report project status and results.

Outcomes (1), (4), and (5) are demonstrated both in the students' project work and in exams, and are assessed based on the results of specific exam questions. The other outcomes are assessed through evaluations of the students' project work. Each week, the student teams submit a formal report on their progress to that point, and each week the teams give brief presentations at Design Reviews. The project culminates in a formal final report (typically about 50 pages for a three-person team), a formal final Design Review presentation, and a demonstration of product functionality, all of which are used to assess the extent to which students have achieved the outcomes listed above.

IV. Course Structure and Content

The ECE Design course is broken into clearly separated components. The student teams work relatively autonomously on their designs while class meetings focus on learning about the design process in general terms. That is, the students are not "taught" how to design their specific products, but rather are expected to do the design on their own, with minimal assistance from the faculty, following a sound design process as discussed in class. Topics for classroom discussion include:

- Team dynamics and teamwork strategies
- Problem definition and market research
- Customer requirements and product specifications
- Brainstorming and decision making
- Maintaining an engineering notebook
- Technical presentations and reports
- Business, finance, and return on investment
- Schedule / quality / cost tradeoffs
- ECE design options / tradeoffs
- System and subsystem I/O specifications
- Standards and regulations
- Liability and ethics
- Design for manufacturability
- Schematic diagrams and PCBs
- Intellectual property
- Quality and reliability

Meanwhile, the student teams embark on an original design in response to a design problem statement. The problem statements are sometimes generated by faculty based on perceived needs in the marketplace, and sometimes are proposed by external organizations. Examples of design challenges from the past include:

- Electronic torque wrench
- Electronic kitchen scale
- Solar-powered battery-charger
- Self-leveling balance beam

The student teams are required to submit weekly formal written reports. Each submission is evaluated using a rubric for quality of content, presentation, and writing. The submissions cover the following stages of the design process:

(1) Market research, customer requirements, and product specification
(2) Brainstorming and value analysis of alternative design concepts
(3) Project milestones and detailed Gantt charts
(4) Specification of subsystem interfaces
(5) Design modifications and testing
(6) Final design, including economic analysis

The student teams also participate in weekly Design Review sessions, in which they are expected to give presentations to the faculty and participate in a critique of other teams' designs. During the final week, this presentation takes the form of a final Design Review in front of an external audience, including any sponsors of the design challenges.

The most substantial component of the course, the design work itself, takes place outside of regularly scheduled class times, in open laboratories. Student teams are responsible for setting schedules, maintaining progress, and seeking help when needed. Each team develops a detailed design, orders parts (within a strict budget) from a selected list of vendors through the Department Shop, and constructs a prototype (using a variety of construction techniques of their choosing, ranging from prototyping boards to soldered connections on a fiberglass vector board to custom-ordered PCBs). Typically, each student team is able to demonstrate that at least some of their subsystems perform as designed, and more than half of all teams are able to demonstrate a fully working prototype.

V. Course Logistics and Process

WPI's undergraduate program runs on a calendar of four seven-week terms, and during each term a student typically takes three courses (the equivalent of nine credit hours per term, or 18 credit hours per semester). In keeping with the project education philosophy, courses meet fewer hours than at other universities, and more responsibility for learning is placed on the students. Nonetheless, as do most ECE courses at WPI, ECE Design meets five days per week and requires daily engagement by the students.

At the onset of the course, the students are grouped into design teams of three. Since the ECE program offers a great deal of flexibility, the students enter the course with a wide variety of ECE backgrounds. The instructors choose teams based on student background, so that each team has a balance of necessary skills (analog and digital design, etc.) and a balance of academic strengths. This presents the significant challenge of teams with uneven academic skills, levels of background, and often, levels of motivation.

In order to encourage the design teams to adopt good working habits and develop a successful team dynamic, they receive teamwork training from the Director of WPI's Student Development and Counseling Center. Each team must develop and sign a contract in which they explicate a set of rules for how they will work together, communicate, and handle any conflicts or differences. Each team is advised that at the end of the term, they will be asked to sign a statement apportioning credit among the teammates for the group work. The algorithm for this apportionment encourages equal participation, as students who contribute more than their share do not receive extra credit.

The ECE Design course is team-taught by two or three faculty members. They share responsibility for heading up classroom discussion (although both participate in each discussion, and each faculty member takes the role of "Engineering Manager" for one of the design projects. Between eight and ten teams are assigned to each design project, as is an upper level undergraduate student who serves as "Senior Engineer" for the design teams. The faculty managers hold separate Design Reviews each week for the projects, so that the design teams can react to and learn from each others' work.

In order to encourage a diversity of designs, each team is empowered to develop their own product concept and specifications based on their market research and interpretation of customer requirements and design criteria. Generally, the solutions range considerably in complexity, features, and mix of analog and digital circuitry. The course is consciously not run as a competition; the goal is to develop a rich set of alternative designs, each of which satisfies its own criteria. Although the students learn from each other, the design solutions tend to remain quite distinct from one another.

Each team meets with its Senior Engineer each week, to get feedback and direction, and to report its progress. The Senior Engineer receives a progress report, reviews the team members' engineering notebooks, provides guidance and suggestions, and develops a report for the faculty member overseeing the project. A graduate Teaching Assistant serves as "Chief Engineer" for the projects, providing technical assistance and giving the students detailed feedback on their written work.

VI. Preliminary Results, Current Directions, and Future Work

The ECE Design course has only been a requirement for two years as of this writing, and an initial formal assessment of its impact on the senior design projects (MQPs) will take place during the summer of 2004, when the next regular MQP Review will take place. Nonetheless, considerable evidence exists that the course has made a substantial and positive impact on the curriculum.

Table 1: End-of-course survey results (N=70, 82% response rate)

How many hours did you put into EE 2799 *each week this term, on average?*				
Less than 10	10-15	15-20	20-25	More than 25
0%	***6%***	***26%***	***35%***	***33%***
Pick the phrase that best ***describes your teamwork experience*** *this term*				
Very negative	Somewhat negative	Neutral	Positive	Very positive
3%	***6%***	***14%***	***47%***	***30%***
Overall, ***how much did you learn*** *from this course?*				
Almost nothing	***1%***			
A little	***10%***			
Quite a lot	***57%***			
More than any other course I've taken	***32%***			
Pick the phrase that best ***describes your overall satisfaction*** *with this course.*				
Very unsatisfied	Unsatisfied	Neutral	Satisfied	Very satisfied
3%	***10%***	***22%***	***46%***	***19%***

The ECE Design course has become a "rite of passage" among students, and most have enthusiastically responded to its challenges. Most students report working between 20 and 25 hours per week on the course, compared to an average of about 15 hours per week for previous ECE courses. In a recent anonymous end-of-course survey, with 70 of 85 students responding, 32% of respondents reported *learning more in the ECE Design course than in any other course* they had taken to date. Table 1 presents more results from the survey.

ECE faculty, all of whom advise senior design projects, report anecdotally that students who have taken the ECE Design course follow considerably better design processes than previous students, from development of specifications and design synthesis to simulation, analysis, testing, and documentation. The upcoming MQP review will provide data regarding the extent to which these senior projects reveal evidence of a sound design process, and consideration of economic, ethical, and other nontechnical factors. This, in turn, is expected to lead to refinements and revisions in the ECE Design course.

A recent offering of the ECE Design course[3] involved design problems proposed by the non-profit organization Design that Matters ™. As opposed to designing consumer electronics products for the US market under the model of a large corporation, these students tackled real design problems aimed at users in the developing world. The intention was to help students understand how the work of engineers can address fundamental problems of sustainable development and improve the quality of life for underserved populations.

Two pieces of undone work, both related to the formative nature of this sophomore-level design course, remain. The first is to develop a remediation strategy for students whose experience in the ECE Design course is not successful. In recent offerings, as many as 10% of the students who have taken the course have not passed it, some due to a weak background in the basics, but others due to an unwillingness or inability to participate fully in an intensive team-based design process. Currently, the recourse for these students is to take more background courses and reattempt the ECE Design course. It may be appropriate to develop a more intentional path for these students, especially if the reason for their lack of success goes beyond a lack of fundamental knowledge.

A second task will be to consider how the results of the ECE Design course can be used to guide improvement and revision of previous courses. Since the ECE Design course is the first opportunity most students have to apply fundamental concepts and basic knowledge of ECE, it may provide insight into how the earlier courses could be enhanced. Already, patterns have emerged that suggest certain areas (digital circuits and software) are more readily learned than others (fields, signals, microelectronics), and that this can influence student choice of design strategies. In order for students to choose appropriately from the available design options, they must be able to draw on a broad array of fundamental skills and knowledge. Ironically, the more ECE broadens to include topics beyond traditional fundamentals, the more that good designers must understand those fundamentals, so that designs can be kept simple, reliable, and appropriate to users' needs.

Bibliography

1. Michalson, W.R. and R. C. Labonté, "Capstone Design in the ECE Curriculum: Assessing the Quality of Undergraduate Projects at WPI," *Proceedings of the American Society of Engineering Education 1996 Annual Conference*, Session 1232, Washington, DC, June 1996.

2. Polizzotto, L., and W.R. Michalson, "The Technical, Process, and Business Considerations for Engineering Design," Proceedings of the 31st Frontiers in Engineering Conference, Reno, NV, October 2001.

3. Vaz, R.F., S.J. Bitar, T. Prestero, and N.Cantor, "Student Design for the Developing World," *Proceedings of the ASEE 2004 Annual Conference*, paper 2004-1642, Salt Lake City, UT, June 2004.

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