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Interdisciplinary engineering capstone course sequence designed for career preparation

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Abstract

The engineering senior design year-long capstone course sequence at Seattle Pacific University (SPU) is designed to mimic a high technology incubator and involves students working in interdisciplinary, diverse teams to implement a design project while developing professional skills. This paper will describe the course sequence including the design process, teaming guidance, project ideation, professional skills development; and grading/assessment methods.

Modeled after industry practices, this course sequence includes design sprints, project management, risk assessments and mitigation, formal design reviews by the course instructors, and presentations to industry professionals. Each cross-functional team includes a mix of electrical, computer, and mechanical engineers. All teams consist of students of different ethnicities, genders, and ages. Teams are formed with diversity in mind, but also based on each student's expressed project-type interest. The instructors then lead the students through problem identification, project ideation, and development into an appropriately scaled design that is both challenging and doable.

Much of the course is focused on team building and processes, conflict management, and both team and individual reflection on team performance. The instructors emphasize the value of diversity, such as the need for each student's voice to be sought, heard, and respected. The professional skills developed in the course include project management, both formal and informal presentations to varied audiences, formal documentation, budgeting, business cases, and consideration of ethical issues related to their specific project.

By emphasizing not just the project itself and the technical skills, but also focusing on professional skills in interdisciplinary, diverse teams, the course structure touches on aspects of each of the ABET 1-7 student outcomes.

While it is a struggle to keep the workload manageable, employers and alumni frequently remark that this sequence prepares the students well for their future careers.

Introduction

In its current form, the engineering senior design year-long capstone course sequence mimics a high technology incubator in which students work in teams to implement a design project over nine months. The course sequence combines many of the valuable capstone course components utilized by other schools, such as entrepreneurism, interaction with industry, multidisciplinary teaming, diversity, and professional development.

This sequence of three courses (EGR 4811, EGR 4812, and EGR 4899), which are closely linked, offers an example of a capstone that touches on all ABET 1-7 expected student outcomes [1]. Table 1 shows a mapping of various aspects of the course to these expected student outcomes. The paper expands on these aspects of the course, and Appendix A provides more written description of this mapping.

Table 1. Map of the ABET expected student outcomes to various course aspects.

	Related ABET outcome #						
	1	2	3	4	5	6	7
Project identification, ideation, scoping (entrepreneurial)	X	X		X	X		X
Specifications and project risk reduction prototype	X	X	X	X		X	X
Considering stakeholders (entrepreneurial)		X		X			
Design reviews	X	X	X		X	X	
Project management					X		
Product risk assessment and mitigation	X	X		X		X	
Communicating the design (various audiences, including industry)			X				
Reading Club (professional development)			X				X
Budgeting				X			X
Multi-disciplinary teaming					X		
Diversity and Inclusion activities and emphases			X	X			X
Ethics scenarios and discussions		X		X			
Project Impact paper		X	X	X			

Here are the 7 ABET expect student outcomes.

Graduating seniors will have…

1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors
3. an ability to communicate effectively with a range of audiences
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts
5. an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Brief background of the senior design sequence

The engineering capstone course sequence has evolved over more than three decades. Initially, electrical engineering was SPU's only engineering major with a capstone project. It focused on team design projects but did not include close teaming guidance or connections with industry professionals. The presentations and documentation requirements mid-project were less formal and directed only to the course instructor. Later, we added in more formal design reviews with the course instructors as well as presentations to industry professionals at the year's end. We also added the computer engineering major, so these majors teamed with the electrical engineers.

About 15 years ago mechanical engineering became a major offered at SPU, and these students joined the senior capstone projects, making the teams truly interdisciplinary. Since then, we have also increased the emphasis on specifications and regular formal design reviews as well as introduced quad charts [2]. (The "Quad Chart" is used widely in industry to provide a 5-minute summary of a project to executive management.) During this time, we also began having the students present their work to industry professionals mid-way through their projects as well as at the end. All of these will be described in this paper.

More recently, we changed the sequence to have a strong entrepreneurial bent. Now, near the beginning of the year, the newly formed teams are involved in an 'ideation day', followed by a quarter of project risk reduction. Toward the beginning of the project, the students also present their projects to industry professionals, and field questions from them. This is repeated mid-way through the project and at the end. Table 2 outlines the contents of the current three-course sequence.

Situating our work in the literature

Older papers in the literature focus on the novelty of industry sponsorship of capstone projects (e.g., [3] and [4]) and the need to teach teaming to students (e.g., [5] and [6]). Some of the projects in the capstone courses do have direct industry sponsorship, but most of the projects arise from each design team's ideation. We have found over the past 20 years that students generally engage more fully and passionately when they have developed their project idea from scratch. This provides students the opportunity to engage in "needs-finding", an important opportunity indicated by Howe and Goldberg [7]. As for teaming, we agree with the literature that effective team functioning is crucial to the successful completion of a project and that learning effective teaming skills is a key outcome of the capstone course sequence. Thus, the courses certainly include careful team guidance.

Several recent papers discuss engineering capstone approaches that focus on two key aspects of the capstone course sequence: implementing multi-disciplinary teams (e.g. [8], [9], and [10]) and including entrepreneurial aspects to the capstone (e.g., [11] and [12]). Howe and Goldberg [7] reveal that, in their 2015 survey of engineering capstone courses, 52% of the respondents indicated that their courses included faculty and/or students from at least two different disciplines, though only 11% had at least five disciplines represented. So, the formation of teams that include several different engineering majors is somewhat common. As for entrepreneurism, unlike some capstone courses that focus on the full entrepreneurial process [11], ours focuses mostly on the ideation and stakeholders aspects of entrepreneurship, as will be discussed later in the paper.

Table 2. Sequence of key program elements in senior capstone course.

EGR 4811 Fall Quarter	• Problem area research and interest survey • Team formation, norms, contracts, assessments and reporting • Project ideation, research and development, mission/vision • Project refinement – customer design priorities, key characteristics diagrams • Risk Reduction Prototype – specifications, analysis, safety, project plan • Mid-term: Design Review 1.1 (like Initial Tech Review) documents, PowerPoint • Engineering Advisory Board presentation and feedback • Fabrication of Risk Reduction Prototype and testing • Final Exam: Design Review 1.2 (like Prelim Design Review) prototype demo
EGR 4812 Winter Quarter	• Full Scale Development, formal engineering documents, final specifications • Ethical scenarios and considerations • Diversity in Engineering – Women in Engineering panel • Mid-term: Design Review 2.1 (like Critical Design Review - CDR) specs and refined project plan • Engineering Advisory Board 2nd presentation for funding, budget performance • Fabrication, ordering materials, initial testing and analysis complete • Final Exam: Design Review 2.2 (like Production Readiness Review - PRR) demonstrate rough working models
EGR 4899 Spring Quarter	• Final fabrication and testing – formal test plans • Reliability, maintainability, operational safety, business case analysis • Risk analysis and Safety Engineering, Interface specifications • Project impact reflection on society, Reading Clubs • Reflection on team and individual learning – assessments • In-house STEM conference presentation • Mid-term: Design Review 3.1 Demonstration to customer. All specs met • Final Exam: Demonstration to public and Engineering Advisory Board

Another salient current topic is the formation and guidance of diverse teams so that they will have an inclusive culture (e.g., [13] and [14]). SPU as a whole, as well as its engineering programs, are now roughly 50% white and 50% students of color. Further, the SPU student body is more than a third first generation to college. We also have a significant percentage of international students (6.8%) and students who are older than 25 (6%). The engineering programs are roughly 20% female, and we have a small number of transgendered students. Thus, the capstone teams are diverse in many ways. Despite the diversity, we recognize that inclusivity does not necessarily happen organically. Thus, we guide the teams in being inclusive, as described later in the paper.

Design process

Project identification, ideation, scoping (entrepreneurial)

Because it is fashioned after a high-tech incubator, the senior design sequence takes the students through all phases of engineering design, from problem-identification to brainstorming potential solutions, to ongoing refinement of those solutions throughout the course. Students encounter challenges with their designs which must be overcome, and often certain features or methodologies are discarded in favor of others.

The project ideation phase begins with interest surveys sent to the students just before the start of the fall quarter. Based on an initial survey with approximately 25 different areas of interest, students are paired with another student having like interests for the first class session. This pair produces up to six “problems spaces” using ideation techniques (Venn Diagrams, Mindmapping, Brainstorming). From these six problem spaces, they will choose one problem and develop it further through brainstorming. They will then come up with three possible solutions for that problem, and through continued development, narrow that down to a single solution idea, which they will expound on using a sketched Quad Chart [2] (more on that later).

For a class of 40 students, this results in about 20 project proposals which the students have devised. To this group of ideas, the professors include additional project proposals from local companies and non-governmental agencies (NGOs) for a total of about 25 project proposals. These are all assembled into an interest survey. It is from this second interest survey that the teams are formed. (See the *teaming* section later in the document for more about the team formation.)

The teams that are formed then choose a problem space and project that they can all be passionate about. Often this takes some iteration and multi-voting and may be entirely different from any of the projects in the interest survey. The instructors provide input at this point around project scope and feasibility, so that the selected project is challenging, yet not too ambitious, and fully exercises the skills of the cross-functional team. When the team has an industry partner, the goals of the industry partner must also be included.

A critical time for project ideation occurs during an all-day Saturday session in the second week of the academic year. Here the instructors interact closely with the teams to develop the initial project ideas and scope. This all-day sprint can put the teams ahead by several weeks compared to the progress made at the once-per-week class and lab session.

Specifications and project risk reduction prototype

The centerpiece of the scoping process is the creation and revision of specifications. The initial set of specifications focuses on what we call the Risk Reduction Prototype phase, which takes place in the first quarter. In this phase, the teams identify and concentrate on the aspects of the project deemed to have the most uncertainty and risk. Students are expected to build relevant prototypes in a rapid prototyping manner that can develop and demonstrate the most complex or risky parts of their projects.

The specifications for the full project are developed early in the winter quarter and become a contract between the teams and the instructors as to what they commit to deliver by year's end. Another Saturday design sprint is set aside early in Winter quarter primarily for firming up the specifications. Their final grades will rest partly on their performance against these specifications, and so all team members and the instructors sign the document once the agreement is reached. The negotiation around the specifications provides an opportunity for the instructors to shape the complexity and challenge of the projects. In some cases, teams are too optimistic about what they can accomplish, and the instructors must help reduce the scope of the project. In other cases, the project is not adequately challenging, and the specifications become one of the vehicles to enhance the scope of the project.

Considering stakeholders (entrepreneurial)

A key aspect of the specifications is the consideration of the project's stakeholders. In most cases, there are multiple constituencies for a given project: investors who fund the development, end-users, NGO's that purchase the device, etc. Where there is no industry customer for the design team, the professors play the role of the customer/investor in demanding certain levels of performance, efficiency, safety, and cost-effectiveness.

Design reviews

Formal presentations are held twice each quarter in the form of Design Reviews. These constitute the students' mid-term and final exams, following a strict sequence with required engineering products. These Design Reviews roughly follow the gated design process used in many industries and approximate such gates as Initial Technical Review (ITR), Preliminary Design Review (PDR), Critical Design Review (CDR), and Production Readiness Review (PRR). Each student on the team is expected to participate in the review and present part of the engineering documentation.

The design reviews are structured to move the teams through the design process, and depending on the stage, will emphasize such things as standard engineering documentation, project plans, specifications, and even demonstrations. The documentation is a key component of these design reviews, including block diagrams for mechanical, electrical and software; circuit schematics; mechanical CAD drawings; references to formal standards; PCB layouts; electrical wiring diagrams; etc.

After the Fall and Winter mid-quarter design reviews the teams present their progress to our industrial advisory board. After their presentations, the board challenges them with questions about their projects and provides them with technical advice based on the members' various areas of expertise.

Project management

Although the pace and timeframe of the classes favor a design sprint modality, the course does require the students to engage in aspects of traditional project management skills, including use of Gantt charts (most commonly using Microsoft Project). At the end of each class period, each team is required to give a status of their project during a short "Stand-up Meeting", commenting on where their project is in sync with the plan and where it is diverging. These are designed to mimic the team stand-up meetings typical in industry.

Product risk assessment and mitigation

As the students' projects begin to reach an appropriate level of maturity, usually in the third quarter, they are asked to perform a risk assessment for the product. The students then identify several risks with the highest combination of likelihood and consequence, and then propose mitigations for those risks. Students are encouraged to consider technical risks, programmatic risks, and financial risks in this analysis. This assessment utilizes standard Safety Engineering tools and terminology based on a matrix of the likelihood of occurrence and severity of consequences. In some cases, the students incorporate the mitigation into their design or program. Other times, full mitigation is not practical, and the students are asked to discuss why they have elected not to mitigate that item.

Communicating the design

Another vital part of the design process is communicating the design. As mentioned already, the teams write specifications documents, conduct weekly standups, participate in formal design reviews, present to the industrial advisory board, and draft many engineering documents.

The "Quad Chart" [2] is yet another required communication product that the teams must prepare, which is beneficial for both engineering presentations as well as presentations to non-engineers. This gives the students practice communicating with brevity and impact. The maturity of this Quad chart evolves throughout the year as the project matures, and teams adjust it slightly for various audiences.

Toward the end of their projects, the engineering design teams present to non-engineering audiences at our university's STEM-focused research and design fair in the spring quarter. In this in-house conference, students from various STEM disciplines present their research and design projects from classes and internships. Each senior design team is required to either hold a poster session or make a presentation. Most of the audience for this comes from non-engineering fields, so the students must explain their projects in common terms.

Each year, a team or two will also choose to participate in our Business school's Social Venture Plan Competition (SVPC). For SVPC, the students work with a cross-disciplinary team to develop marketing strategies, business cases and a technical brief. Since these presentations are focused on the social and business aspects of the project, rather than the technical aspects, the students gain even more experience considering their projects from multiple viewpoints.

The culminating communication event happens at the Design Fair held at the end of the academic year and just before graduation. The students assemble their projects in the lobby of the engineering building and the doors are opened to the whole campus community (fellow students, professors, administrators) as well as the engineering advisory board and the public. This represents perhaps the strongest motivation for the students to deliver an attractive and functional product.

Professional practice preparation

Aside from emphasizing the full design process, the course sequence also aims to prepare the students for professional practice.

One mechanism for exposing the students to the broader professional environment is through the "Reading Club". A wide range of books is offered to the students at the start of the winter quarter, from which they must choose one to read. These books are generally not engineering-related, but deal with subjects such as leadership, teamwork, project management, motivation, global poverty, diversity, integration of faith and profession, technology and the changing nature of work, etc. Students must read the book, discuss it together, and meet with their professors as a group to report on their reflections. This is designed to raise the conversation above the mere technical aspects of an engineering career and foster a broader sense of life-long learning.

Other important aspects of professional practice that support design include budgeting, teaming, diversity & inclusion, ethics, and project impacts. These are described below.

Budgeting

Money is a key aspect of a design. Funding for capstone projects is an area of significant variation among capstone courses nationally [7]. In our program, a two-phased funding approach is used, which augments their communication and persuasive skills. Each team is allocated a baseline funding amount. They are informed that they will have an opportunity to "pitch their project to interested investors" for additional funding. These investors are, in fact, the university's Engineering Advisory Board, which is tasked with distributing endowments funds (designated for student projects) based on team requests and project quality. The students gain the experience of having to "sell" the worth of the project through a presentation to the Industrial Advisory Board members.

Teaming

The teams are formed using a multi-step approach. As mentioned above, there are two rounds of interest surveys. It is on the basis of like-interests defined by the second survey that the year-long teams are formed. From this matrix of interests, the instructors attempt to create teams of 4-6 students with as many overlapping interests as possible. Another major criterion of team formation involves creating a fully cross-functional team consisting of mechanical engineering students, electrical engineering students, and computer engineering students. Once teams are narrowed by interest and major, the instructors attempt to address gender and racial balance. Instructors also need to consider what is known about the students in terms of their leadership ability, academic and manufacturing capabilities, etc. (The senior design course sequence follows a junior design course, so the instructors of the junior design are often consulted at the team formation stage since those instructors are familiar with the students' strengths and weaknesses.) This is a complex matrix of considerations to balance. Even so, the success or failure of the teams to achieve all of their objectives by year's end can often be traced to this initial, critical composition.

The development of team skills is one of the primary objectives of the capstone course. Instructors expect teams to go through all the phases of team "forming, storming, norming and performing," and expect there to be conflict along with the over- or under-utilization of some team members. Many of the teams experience under-performing team members and must resolve the extra workload this causes for the others. The teams are encouraged to try to deal with these issues internally, but always with the promise that instructors will become involved if the team fails to resolve them satisfactorily. The instructors emphasize that team conflicts are not unusual, and the preference is that the teams experience these and learn strategies for resolution in this supportive environment. The goal in the course sequence is to both lessen the struggle (through frequent dialogue and interventions when necessary) and to help them to expect conflict and learn to manage it effectively and respectfully.

There are several points throughout the year where we invite the students to reflect on their qualities as a team member. We ask the students to describe themselves as a teammate, from both positive and negative perspectives. We provide them with a list of adjectives and short descriptors to which they can either aspire or identify. This assignment is not graded based on the degree of positive attributes, but rather on candor and self-reflection.

Diversity and Inclusion

Our Engineering and Computer Science Programs' mission statement reads in part that we are a "diverse and supportive Christian community," and our engineering program is more diverse than the national average in terms of race and gender. But that certainly doesn't guarantee that all students feel included. Therefore, the course sequence aims to facilitate and model supportive inclusivity in various areas, such as ethnicity, cultural identity, religious beliefs, gender, age, ability/disability, socioeconomic status, life experiences, etc.

In our view, the senior design course sequence is doing some things well, including a) team forming and building, b) hearing the students' voices, c) holding discussions about diversity in engineering, d) developing student presentation skills, and e) allowing students to utilize their individual strengths while addressing their weaknesses. This section will discuss each of these, and then it will present the near-term plans for improvement.

Before we discuss those areas, we deem it important to define the terms, ‘diversity’ and ‘inclusion’. We will use ABET’s definitions [15].

> Inclusion is the intentional, proactive, and continuing efforts and practices in which all members respect, support, and value others. An inclusive environment provides equitable access to opportunities and resources, empowers everyone to participate equally, and offers respect in words and actions for all.
>
> Diversity is the range of human differences, encompassing the characteristics that make one individual or group different from another. Diversity includes, but is not limited to, the following characteristics: race, ethnicity, culture, gender identity and expression, age, national origin, religious beliefs, work sector, physical ability, sexual orientation, socioeconomic status, education, marital status, language, physical appearance, and cognitive differences.

a) The first area in which we are doing well is in forming the teams and providing teambuilding activities. Engineering teams in the workplace are inherently diverse, so we set students up for future career success by forming diverse senior design teams and later assist in facilitating team building, conflict mediation, and team reflection. As explained earlier in the teaming section, when forming the teams we consider how the individuals can use their diverse backgrounds to benefit their team. After the teams are formed, the course integrates team-building exercises, such as Saturday intensive design workshops, where students invest in getting to know their team even while they are taking the first steps to design their product. Students are asked every quarter to provide a written reflection on themselves and their team. One of the benefits of a written assignment is that during reflection, students often come up with their own solutions, or after seeing it in writing, realize that they need to ask for help.

b) The instructors emphasize the value of diversity, such as the need for each student’s voice to be sought, heard, and respected. We strive to hear the voice of the individual, the voice of each group, and the voice of the class as a whole. The professors intentionally schedule meetings with individual students (one-on-one’s), meetings with each team as a whole, conflict mediation meetings, and intervention meetings (when needed). There are also informal “check-ins” each week during class and lab time. By facilitating these meetings, we provide a platform for each student to express what is going on in their uniquely difficult lives and find solidarity with their engineering community. Finally, we request anonymous feedback on the course at the end of each quarter to provide an alternate forum for their voice to be heard.

c) In addition to teamwork and communication, we also embed diversity content in the curriculum. A highlight of the year is when we invite guest speakers to talk about their experiences as women in the engineering workplace. Hearing about how women have been and continue to be treated as engineers is an eye-opening discussion for the students. We also include practical applications for the students. For example, we discuss what they should do if they see someone disrespecting someone from an underrepresented group in the workplace. Another major theme in the course is ethics, where we study ethical dilemmas and engineering ethics case studies that have diversity issues embedded within. Lastly, as described above, we ask the students to choose to read a book from a list of 20 pre-approved titles that emphasize ethics and/or diversity in engineering. Within those choices, four of them directly relate to diversity, and these are among the most popular.

d) A fourth area of diversity that we have prioritized is the degree to which every student is comfortable making presentations. Though this is an important skill for engineers, some students find this very intimidating. We have found a solution to be frequent presentations in a welcoming environment with only minor grading consequences. For the weekly stand-up meetings described earlier, usually, only one member of each team will present. However, they must rotate through the whole team across the class periods. In this way, even the reticent students get an opportunity to practice their technical presentation skills in an informal, "friendly" environment. This prepares them for the higher stakes design reviews and the more intimidating public presentations.

e) The last area of diversity we want to discuss is the emphasis on using each student's gifts, talents, and experiences, and at the same time providing a space where they can work on their weaknesses. For example, student strengths related to areas such as leadership, mathematical and theoretical skills, hands-on practical skills, project management, etc., can be helpful in assigning team roles. The comprehensive nature of this course sequence allows for equity in contribution and grading, in that students have multiple ways to shine depending on their strengths.

Toward the end of this academic year, we plan to strengthen our approach to diversity and inclusion by incorporating a mentoring program, inviting guest speakers that reflect the students' diversity, and providing mediation training, as described below.

First, it was our engineering student council that recently requested a capstone mentoring program as a way to empower students as they develop and engage with their diverse community. So, this Spring, we will pair a senior design student as a mentor with a junior design student as a mentee. The mentorship program will provide the opportunity for both students in the mentoring pair to have a better sense of purpose and belonging in the engineering capstone community, while each student helps prepare the other for their next chapter in life. Junior design mentees will hopefully gain increased confidence by having a sounding board, an unintimidating student teacher, and early exposure to the senior design experience. Senior design mentors will hopefully gain a sense of pride by giving back to their community, increased understanding by teaching, and leadership experience as they prepare for their careers.

Second, because of diversity statistics in engineering industry, most of us know white male engineers or project managers, so it is easy to ask those people to visit as guest speakers. However, representation matters, and we want to have guest speakers who look like our students and who have similar backgrounds to them. We are actively working to improve our networking with diverse engineers who can connect with students who might otherwise feel like they don't belong in engineering. In other courses at our university, we have invited diverse guest speakers, and we received student feedback that the students appreciated the representation.

Finally, though it is well-recognized that diversity can improve a team's final product, it is also well-recognized that diversity can lead to conflict and to some students feeling like they don't belong in the group. Our instructor-provided conflict mediation has diversity at heart, in that the instructor values each student's background and experiences and seeks out the individual student voices. However, during the Covid-19 pandemic which prevented regular in-person work, the instructors were not aware of ongoing team conflicts and were not able to intervene early. Though we now can again monitor the teams in person, the pandemic revealed that it would be beneficial for students to be trained to manage their own conflict mediation, thereby creating their own sense of belonging and self-efficacy in a diverse group. This training could utilize Patrick Lencioni's book, The five dysfunctions of a team [16], and possibly include a workshop led by a faculty member from our university's organizational psychology program.

Ethics

For the past three years, an intentional ethics module has been added to the course beginning with a case study [17] around the American Society of Civil Engineers Code of Ethics [18]. The professors then design ethical and product safety scenarios based on the student's own senior design projects. These scenarios attempt to cover most, if not all of the 7 Ethical Canons found in the ASCE Code of Ethics [18].

Students are confronted with their scenario during a class session and have only a couple of minutes to consider their response. The professors play the various roles of an angry customer, a federal regulator, a dishonest international shipping agent, etc. This way, the whole class gets to observe the scenario and the team's response to that scenario. The class is then invited to discuss the various aspects of the scenario as they relate to the ASCE Canons and the effective or ineffective aspects of the team's response.

The ethical emphasis is not limited to the module or the case studies, but permeates the discussions in areas such as the specifications document, particularly when considering product safety and integrity of performance claims.

Project Impacts

Near the end of the course, just before graduation, each student writes a "Project Impact" paper in which they discuss the impact of their design project (1) globally, (2) economically, (3) environmentally, (4) socially (this includes reconciliation and justice from a variety of standpoints), and (5) in local communities. The instructors find that this paper elicits some of the most profound self-reflection of the program. The students are often deeply personal, linking their project to their values and aspirations.

Industry involvement

A small number of the senior design projects are sponsored by industry. For some others, we connect the design teams with an industry professional for expert insights when needed. Otherwise, industry interaction for most teams takes the form of the students preparing recordings describing the current state of their projects at three different points in the three-quarter long sequence: once toward the beginning of the project, once in the middle, and once at the end. We then share these recordings with our industrial advisory board who views those recordings in advance of an advisory board meeting. Then, at the meeting, the board interacts with each team to ask them questions that they deem important from their experience and knowledge. Often, the teams have already considered the concern in question. Other times, though, the advisory board member brings new considerations for the team to tackle. Frequently these are in the realm of safety, power needs, or alternative ways of accomplishing a project's function.

For those teams that have industry partners as customers, they receive an additional wealth of considerations such as real market forces and the need to execute Intellectual Property Agreements. The teams are coached on creating outcome specifications that matter to the customers, in addition to internal performance specs which may support those performance goals.

As mentioned above, we very much value industry interactions for the teams, but we also value autonomy for the teams to follow their passions and to learn the impacts of their ideation and project scoping. We are continually aiming to fine-tune this balance.

Grading/ student assessment methods

Our grading approach in this course is an attempt to wean the students from grades based on percentages to a more common assessment method used in industry. Students are assessed as to whether they "meet expectations", "exceed expectations", "far exceed expectations", "meet some expectations" or "do not meet expectations". These translate into a 0 through 4 score on most of their work. Consequently, "meeting expectations" is a 2 out of 4 which shows up as a 50% in their learning management system. However, an average of purely "meeting expectations" translates into roughly a "B" for a final quarter grade. Though this creates some anxiety and lack of granularity through the course of the quarter, the students have consistently agreed to continue with this system, understanding that it is much closer to the kind of evaluation system they likely will face in industry.

We also strive for the students' final grades to be a mixture of team scores and individual scores. This prevents a student from fully skating by on their team members' work but also holds each student accountable for the entire team. The individual score can result in a full letter grade higher or lower than their baseline team score (or even more than a letter grade in extreme cases). In addition to these assignment scores, the instructors use a variety of other evaluations along with input from fellow team members to nudge the grade higher or lower.

These other evaluation tools include an "Individual Assessment of Team" where each team member is invited to grade their team on a variety of attributes and commitments, which they participate in designing during the early days of the course sequence. The team grade is informed by a "Team Assessment of Team" document, crafted by the team as a whole, where they arrive at a composite score across the same metrics. The instructors meet with each student individually and with each team corporately to go over these assessments. The individual comments and feedback are confidential, giving the student freedom to be candid about their own performance or that of a teammate.

Additionally, the students are required to complete a self-assessment of their progress as engineers, aligned precisely with the 7 ABET expected student outcomes [1]. In this case, their grade for the assignment is not based on a particularly high or low self-score, but rather on their interaction and candor with the objectives. This assessment is discussed during the individual meetings with students as a way of developing an improvement strategy for any areas in which the student feels weak. This self-assessment is conducted both at the beginning and near the end of the academic year to gauge progress in any highlighted areas.

Assessing the course sequence

To assess the course sequence itself we use multiple approaches. One of these is the ubiquitous end-of-course student feedback forms. More unique to the capstone course sequence, though, is the feedback from our industrial advisory board (and industry sponsors for certain teams) after they have interacted with the teams multiple times over the academic year. Also unique to this course is the insight gleaned by the faculty as they interact with each student and each team at regular intervals. Here the faculty observe everything from the stressors to the activities that seem to produce the most student growth. Further, our fellow STEM faculty provide feedback after they observe these design teams at our university's in-house research and design conference.

One common aspect of the feedback from the students (and the engineering faculty) is that the scope of the work is large even though it is a year-long course. It is an ongoing struggle to keep the workload manageable (see the subsequent Future work section). We are hesitant to scale back much since employers and alumni frequently remark that this sequence prepares the students well for their future careers. Our alumni often tell us that their early careers are 'just like senior design'. Thus, the capstone sequence is effectively preparing our alumni for careers in industry.

Future work

While there are many strengths of the current capstone course sequence, we recognize that there are areas needing improvement. Supporting diversity and inclusion will be an ongoing process, and we will continue to learn as a faculty about best practices for doing this and then incorporate these. Other areas also need improvement, which will be discussed in this section.

First, we plan to connect the software engineering capstone course sequence, required for computer science majors, with the engineering capstone course sequence. This will strengthen both capstones as described by Froyd et al. [19], who claim that interdisciplinary teams, even teams with students outside of engineering, "fit well into design courses and are strong motivators of many students." Since computer science students tend to have a different way of communicating, significantly different training, and significantly less teaming experience, this will very much add to the interdisciplinary nature of the projects. Adding software expertise to the teams also provides the opportunity to reduce workload for overloaded electrical and computer engineering students.

Second, we have noticed that an increasing number of students do not have experience in basic building techniques, which hurts teams' workloads and motivation. We are not suggesting engineering students become proficient crafts and tradespeople, only that an introduction to more tools and practical skills could improve the final physical projects. In junior design, instructors are planning to incorporate hands-on lessons in carpentry basics and both electrical wiring and conduit installation. In senior design, instructors can provide further project-specific lessons for teams, like plumbing, masonry, etc. By teaching them how to build first, we can improve efficiency by preventing many building mistakes that take unnecessary time (and budget) and frustrate students.

Third, as described earlier in the industry involvement section, we engage with our industry partners quarterly. However, we are also interested in more frequent feedback by partnering with an appropriate industry mentor for each team. Students could ask their mentor about product-specific and project management questions, and the mentor could provide practical advice to the teams. Potentially, this efficient feedback loop could also help students gain additional practical professional skills, appreciation for global industrial concerns, and start a good habit of regular check-ins with a mentor.

Finally, we will continue trying to reduce the workload for faculty and students while retaining the best features of the current course sequence. To accomplish this, one idea is implementing a flipped classroom. Froyd et al. [19] claim that a student-centered, active learning experience during class time could provide improved productivity in a caring and supportive environment. Instead of listening to lectures during class time, the students would participate in inquiry-based discussions, team building, training, and meetings with the instructors. Flipped classrooms require an initial upfront investment of time and effort by the faculty to create lecture recordings and class activities, but, once developed, the faculty member can re-use the recordings and readings to free up in-class time for interaction with the teams which would otherwise need to be done outside of class time. Also, if the students will fully engage the recordings and readings on their own time, then this will free up time when everyone is in one room for focused work on what otherwise would be group homework and out-of-class meetings. This allows the faculty to be present while the students do their group homework, which streamlines the process and saves the students time.

We continue to be vigilant to find more ways to reduce the workload for faculty and students.

Conclusion

In this paper, we have described our year-long engineering senior design capstone course sequence that includes entrepreneurism, interaction with industry, multidisciplinary teaming, diversity, and professional development. In doing so, we have provided an example of a capstone design course sequence that touches on all ABET 1-7 student outcomes and prepares our graduates for careers in industry. We will continue to tweak the course sequence to make improvements regarding diversity and inclusion, fine-tuning the industry involvement, and limiting the workload.

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Appendix A Summary of program congruence with ABET expected student outcomes

The 7 ABET expected student outcomes [1] and the program elements that support those are described below.

1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.

   Students engage in the design process from ideation through refinement to prototyping and ultimately fabrication and presentation of their solution. This requires significant analysis using all of their tools gained throughout their course of studies. These design projects typically focus on societal needs that are inherently complex and multifaceted.

2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.

   Students must identify a real-world problem, and devise a product that will meet that need, taking into consideration the specific context. Though their concept may morph through the course of design, it must ultimately satisfy specifications that prove that usefulness. Instructors and partners place emphasis on sustainability, appropriateness, and ethical outcomes in the design and execution of each project.

3. an ability to communicate effectively with a range of audiences.

   A plethora of communication opportunities is built into the assignments and class sequence. These include formal and informal oral presentations to a variety of audiences and a large number of written and graphical communications using engineering products widely used in industry. The formal communications events include six "Design Reviews" with engineering "management and customers" having specified materials that simulate the "gates" in the design process. These design reviews constitute the mid-term and final exams for each quarter. Students make a variety of presentations to their engineering peers, to faculty, to *the outside Engineering Advisory Board, and to the campus community at large (Final Design fair and Erickson conference)*

4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.

   We have added an intentional ethics module to the course beginning with a case study from industry [17]. The professors then design ethical and product safety scenarios based on the student's own senior design projects. These scenarios attempt to cover most, if not all of the 7 Ethical Canons found in the ASCE Code of Ethics.

   The students must also reflect on the societal impacts of their project.

5. an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.

   The teamwork component is considered co-equal in importance to the technical content itself and is intensively monitored and discussed throughout the capstone year. We ask the students for individual assessments of the teamwork around a team-devised behavioral contract. Then we ask the team to come together and provide a composite assessment of the team performance based on these individual assessments. Professors then meet with each student individually and each team individually to go over these assessments. The elements of these team contracts include dimensions of collaboration, inclusion, team tasks, goals, and objectives. The team negotiates a set of formal specifications that form a contract with the professors on what will be delivered by the end of the year.

   The course sequence also directs the student teams to use project management tools and frequently compare their project pacing with their project management plan.

6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.

   The first quarter is called the Risk Reduction Prototype phase (RRP) which involves identifying and testing the riskiest portions of their project. This includes both analyses and empirical testing. Students prepare a preliminary set of specifications for just this quarter, to define their RRP objectives. The set of formal specifications created by each team to define what they will deliver by the end of the year will always entail further analysis throughout the year, along with actual testing, which often entails tests for statistical significance.

7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

The students rely first on their prior engineering classes for the background and initial analyses. However, the projects will require them to push into new knowledge areas or go beyond their coursework in existing subjects. Often, their prior faculty can help with this, but there are also times when they must do independent research (such as industry standards). Another facet of this is embodied in the "Reading Club". A wide range of books is offered to the students at the start of the winter quarter, from which they must choose one to read. These books are not strictly engineering-related, rather they deal with subjects such as project management, motivation, and leadership, global poverty, race and gender, integration of faith and profession, the changing nature of work, etc. Students must read the book, discuss it together and meet with their professors to report on their reflections. This is designed to raise the conversation above the mere technical aspects of an engineering career.