Preparation of the Professional Engineer: Outcomes from 20 Years of a Multidisciplinary and Cross-sectoral Capstone Course

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Abstract

The grand challenges outlined by the National Academy of Engineers and addressed by the ABET (Accreditation Bureau for Engineering and Technology) learning outcomes reflect the changing landscape of undergraduate engineering education. Indeed, to be competitive, the next generation of engineering professionals must obtain skills and preparation beyond those in a traditional technical discipline. Accordingly, learners must principally demonstrate the ability to: understand ethics and social responsibility, develop and implement complex systems, communicate and function within multidisciplinary groups, and understand impacts of their designs in different societal and environmental contexts.

Achieving these outcomes requires a pedagogy that not only holistically broadens non-technical aspects of engineering design, but provides a conducive learning environment that is responsive to the changing professional industry landscape. At our University, we have endeavored to facilitate innovation and professional efficacy by closely tying our capstone course with current industry practice. The course begins with as a traditional lecture course in parallel with the problem-based learning format during the first five weeks to rapidly prepare learners for our industry-oriented approach to project management and systems-level engineering, adopted for the remaining 25 weeks. Here, we employ a hierarchical structure that emphasizes both group and individual responsibility for a (self-specified) scope of work. Capstone projects and their associated teams are approved based on how well the nascent student-team can articulate and address the client's need; as such, many if not all projects require multidisciplinary skillsets. Thus, instruction of the capstone course follows a collaborative teaching model, one that is inherent to its success: mixed-discipline learners are co-taught by instructors hailing from respective engineering departments, selected for their broad theoretical, experimental and practical knowledge. We hope to expand in the future and bring in more representation from business, sociology, and environmental science.

This paper critically assesses a multidisciplinary and cross-sectoral engineering capstone course over the last twenty years. During this time, the course structure has evolved to support three main project tracks: corporate-sponsored projects model where clients from industry propose projects for a fee; the social entrepreneurship theme where motivated learners identify opportunities for innovation emphasizing community applications; and the academic or faculty-initiated model, which draws on ideas from on- or off-campus research. Our goal is to create an environment that fosters learner innovation by transitioning students beyond immersive and experiential learning toward actual creation of real-world value, supported by activities specifically intended to foster entrepreneurially-minded learning (EML). By bolstering student contribution in this manner, learners move away from viewing the course simply as an academic exercise. In fact, many successful students obtain further project funding or employment as a direct result of their participation in a capstone project.

The actual realization of these outcomes necessitates significant resources and scaffolded mentorship, fine-tuned over the many years of lessons learned. In this paper, we will articulate the major challenges and revisions to the course along with the motivation behind the current course design, so that other programs may learn from our model. Program assessment will be obtained from faculty and teaching assistant observations, as well as participant feedback.

Introduction

Undergraduate engineering capstone courses represent the culmination of the engineering undergraduate experience, where students apply their accumulated knowledge and skills by working on complex projects, and perhaps more importantly, demonstrate their preparedness to enter the engineering workforce. Depending on specific program requirements, students tackle open-ended projects that are subject to realistic constraints where the solutions, methods or techniques may not be readily apparent [1,2,3,4]. In this way, learners gain the benefits associated with experiential and project-based or problem-based learning (PBL) pedagogies: increased retention of engineering content and process knowledge, complex systems thinking, familiarity with the engineering design process, self-directed ability to acquire new knowledge and apply reasoning, and other skill-based learning outcomes [5,6].

There is an increasing trend to include greater breadth of learning outcomes, learning towards *professionalization*, possibly in response to the introduction of ABET's learning outcomes in EC2000 [1,7]. Engineering programs use the capstone course to introduce or reinforce professional engineering practice, with associated process skills being generally necessary to project success. Frequently, students work in multidisciplinary teams, enhancing interpersonal communication and conflict resolution strategies that encourage peripheral participation across sectors and help formulate the T-shaped individual [8,9]. Teams may be self-selected and self-managed, enhancing motivation and instilling a sense ownership over the project, which ultimately contributes to self- efficacy as an outcome [10,11,12].

However, professionalization in today's global market has taken on new meaning in an industry more focused on dynamic change, innovation and entrepreneurship. The National Academy of Engineering predicted the joint roles of globalization and technological diversity in shaping the engineer of 2020, themes that are also reflected in the 2018-2019 ABET student outcomes [13,14]. There is greater emphasis placed on creative and empathic design inherent to the engineering grand challenges, as engineers are increasingly working directly with consumers. Thus, proficiency in working collaboratively and inclusively to better understand constraints imparted by diverse stakeholders (with sometimes conflicting perspectives) is essential for impactful engineering.

As many of these outcomes are not targeted in traditional, didactic learning environments, employers look for experience among recent graduates, rather than academic performance [15]; more specifically, *real-world* experience that demonstrates the ability to critically analyze a problem, make decisions, and apply theory to complex systems [15,16]. A survey conducted by the American Academy of Colleges and Universities in 2015 found employers agreed that "proficiency in skills and knowledge that cut across disciplines" and problem solving with "peers whose views are different than their own" are important factors in "achieving long term career success." This survey found that less than a quarter of graduates were well prepared in many of these areas: 25% are considered to be innovative or creative; 23% have the ability to apply knowledge/skills to the real world; and 18% have experience working with people from different backgrounds [16]. These themes were similarly reflected in a 2013 survey performed for the Chronicle of Higher Education; over half of employers surveyed also stated that "it is difficult to find qualified graduates [15]."

In ABET accredited engineering programs, the capstone course fulfills the criterion that engineering curriculum must include "a culminating major engineering design experience [14]." This experience, for many undergraduates, represents the predominant or sole interaction with authentic engineering design. Learners enter their senior year with varying levels of preparation, such that certain foundational and process skills must first be *taught* in order to provide a framework or toolbox from which these skills can then be *applied*. As a result, differences between programs dramatically affect the overall student experience, namely, the nature of projects and degree of learner autonomy and support [3,11,17]. This is especially true in a multidisciplinary program; thus a full year capstone experience may be warranted in an engineering curriculum. If course pedagogy allows, the capstone experience could serve to facilitate the real-world experience desired by employers.

In this paper, we examine **twenty years of an engineering capstone course that has strived to follow and evolve with industry practice**. The course's predominant theme has always been to provide learners with an authentic design experience; the term authentic is defined by instructors as "offering real-world impact for an identified customer base." This paper describes the major and minor curricular changes and lessons learned over the years that have shaped course pedagogy to emphasize scaffolded learner preparation to support efficacy in holistic engineering design.

Senior Design Capstone Pedagogy

The senior design capstone course at the University of California, Santa Cruz (UCSC) has changed significantly over the twenty years since its inception as a one quarter, computer engineering capstone, though its fundamental tenets have remained constant: 1) to provide students with an authentic engineering design experience directly adapted from industrial practice and 2) to employ a diverse teaching team where each instructor's contribution shapes course pedagogy. Together, these two objectives formulate a fluid, living course that emphasizes *student-centered learning*. Indeed, progressive years have served to consolidate our client-oriented model to engineering design, allowing the course to remain current with industry practice and position an increasingly growing senior class for efficacy upon graduation.

The term "authentic engineering design" must therefore be unpacked as its definition is rich with nuance that espouses variations in meaning among practitioners and over time. In the literature, performing authentic engineering (qualified as open-ended/real-world, yet within constraints) is to follow the engineering design process; another construct that varies with the practitioner [7,12,14,18]. During lectures, we define engineering as a *top-down process*: "directed problem solving comprised of iterative design that optimizes specified constraints." Yet this high level definition is ambiguous; it leaves much open for interpretation and does not readily engender a design experience appropriate for the novice engineer. Learners electing to build a "cool device" or other such object as their culminating project are not able to ground their design within realistic constraints. These teams struggle to define the prototype's application and also the criteria for success. In contrast, problem-based learning pedagogies are effective teaching models, specifically due to extensive scaffolding allowing learners to navigate complex domains by reducing cognitive load. However, the consensus among the teaching team is that neither of these models can be considered 'authentic' without serving a defined need *for a real-world client*. This requires a fundamental shift in learner mindset, where emphasis is placed on effectual thinking over prescriptive.

Senior Design Projects (SDP) at UCSC requires student teams to identify opportunities for value creation in the world around them which ultimately governs the criteria for evaluation of their project deliverable at the end of the year: a working prototype. Three project themes or program tracks have emerged over the years of course development, which are in keeping with current industry practice: Research, Corporate, and the newest track, Entrepreneurship. Each theme primarily associates with an individual social sector: Academia, Industry, and Business (both for-profit and non-profit), respectively, and are supported by various activities throughout the year targeting acumen relevant to the three communities of practice. Such importance is attributed to the identification of a client or customer base that self-conceived project-teams without a targeted consumer are either asked to rethink the concept or are not approved.

By guiding learners toward the entrepreneurial-mindset with real world application and accountability, the program endeavors to make the complexities of authentic engineering design more tractable, bringing tasks within the learner's zone of proximal development [19,20]. The instructor's role is that of a mentor and facilitator, never the client, to scaffold this transition and make the process attainable. Below is a list of targeted learning outcomes, where the successful student exhibits the ability to:

- Translate in-classroom theory into real world design using professional practice
- Practice critical and complex-systems thinking
- Demonstrate an increased ability to navigate ambiguity and uncertainty
- Self-manage to gain new knowledge, evincing self- and group-efficacy
- Engage diverse stakeholders by communicating and working across disciplines and sectors
- Understand ethics and professional responsibility
- Identify societal challenges, articulate constraints governing *sustainable* solutions, and understand their impacts in social, economic, environmental and technical contexts.

Part 1: Program Design

The University of California, Santa Cruz EE-CE capstone course is a three quarter, 15 unit sequence taught as a mixed-discipline, industry style course. Students are each expected to contribute 15 work-hours per week working on their project as a team for a total of 30 weeks. The course satisfies graduation requirements for Electrical Engineering (EE), Computer Engineering (CE), Robotics Engineering and Bioengineering and is only open to seniors, though it parallels and interacts with two other multi-quarter courses that enhance the project experience by facilitating (more) interdisciplinary teaming: Computer Science Senior Design and Impact Designs: Engineering Sustainability through Student Service. Students are required to enter the course having satisfactorily completed Analog Electronics as well as a significant upper-level design course in either Mechatronics, RF Hardware or Microprocessor Systems. In addition, the course satisfies the Disciplinary Communication General Education requirement; thus, learners must have satisfied Entry Level Writing and Composition.

Preparation

The first quarter of the sequence, normally taught in fall, is devoted to acclimating learners to the industry management model. The quarter begins in a highly structured lecture format with designated class times and assigned (mock) project teams (discussed later in detail). Lecture topics correspond to project framing activities which are applied to the mock project with clear, ordered deadlines and direct instructor feedback. Around week six, instructors begin the transition to the role of facilitator while students self-assemble into capstone project teams. At this point, one lecture session per week is dropped in favor of the management style meeting where instructors meet with individual teams to discuss progress on the quarter deliverables. Note that these *instructor*-run meetings are used to exemplify expectations for the weekly *team*-run meetings that fully constitute the instructor-learner interaction for the following two quarters. Figure 1 depicts the most recent fall quarter schedule in detail: example project pitches (yellow), lecture topics (orange/blue) and homework assignments (green). The primary deliverables for the fall quarter are feasibility studies first for the mock project and then again for the capstone projects, which are framed by activities in the design tool: "SDP Guide to Project Framing and Design."

Week	Monday (projects)	due	Wednesday (professional develop)	due	Friday (technical)	due
0			Introduction: Meyer Briggs personality types & IQEE		Mock Project Introduction	
1	Pitch: Mock Project Q&A		Chp 1: Teamwork & Engineering Design		Block Diagrams & Engineering Systems	
	hmwrk: rapid incubation discussion prompts	Friday	hmrk: Application to mock project	Friday	hmwrk: block diagram for system (team)	1 wk
2	Pitch: UVLED; In-home Aeroponics; Obstacle Detection for Blind		Human-Centered Design; IDEO Video		System Sizing: Power Budget	
			hmwrk: annotated bibliography (team)	1 wk		
3	Pitch:Solar Water Treatment; NonFerrous Waste Sorter; Gas Meter Upgrade		Tools: Criteria Matrix and Design Evalution		System Sizing: Power System Safety	
			hmwrk: Criteria Matrix and Pugh Chart (team)	1 wk	hmwrk: Resubmit block diagram (team)	Wed.
4	Pitch: CubeSat; Pneumatic Actuator Control; Portable Diagnositics		Pitch: Underwater Optical; Electronic Pill Dispenser		Data Sampling and Error Analysis	
			Project Funding: Grants		hmwrk: Flowchart w/ impact assessment (team)	1 wk
5	Pitch: Solar PCB; Smart Behind-the-Meter; Portable Diagnostic Point-of-Care		Teamwork and Roles; Project Management		Review Homework Assignments	
6	Pitch-Autonomous Bulldozer; MultiLingual Engine; Seal Heart Monitorproject time management		Gantt Chart and Project Planning		No Class	
			hmwrk: Application to capstone project	Friday	mock project proposal resubmit due	
7	Instructor-run meeting with Teams		Gantt Chart Review: Post-Implementation		Appropriate component selection: microcontrollers	
	hmwrk: design notebook & team charter assigned	3 wks	hmwrk: mock project reflection	1 wk		
8	Instructor-run meeting with Teams		Engineering Ethics		No Class	
			hmwrk: case study reflection	1 wk		
9	Instructor-run meeting with Teams		Effective Written Communication		Survey of Skills for Employers, IP/NDA/patents	
	team charter due					
10	Instructor-run meeting with Teams		Effective Verbal Communication		Expectations for Winter & Spring	
	project proposal due/design notebook					

Figure 1: Idealized fall quarter schedule for Senior Design Capstone

In-class Lectures and Activities:

This preparatory component to the course is taught in a large lecture hall where instructors introduce concepts relevant to professional engineering practice. Lecture topics fall under three main categories, with each theme generally taught on the same day each week. Mondays are reserved for **Project Pitches**: potential project sponsors from industry, academia, the local municipality or the students themselves come and pitch their project ideas to the class. Students have the opportunity to discuss the project with the presenters, ask questions, and can begin to gauge interest among their peers. Project briefs, compiled by the sponsor, are available to all students before the pitch. These are made accessible through our own custom Drupal 7 CMS module engine, "Senior Design Project (SDP)", created to facilitate the team formation process, track team progress, and serve as a repository for documentation from past projects. The first project pitch is an exception. This is reserved for the client of the mock project, which is used to contextualize the lecture by providing learners practical experience.

Special topics in project management and professional development are discussed on Wednesdays. Here, we cover *professionalization*: project framing, literature review, impacts assessment, written and oral communication, time management, grant writing; *teamwork:* personality types, leadership, when and why to form teams, member roles; *innovation and entrepreneurship*: divergent/convergent thinking, value creation, stakeholder mapping, customer discovery, failure and recovery, IP and patents. The lecture sequence closely follows and is complementary to the accompanying *SDP Guide to Project Framing and Design*.

Fridays are used for **technical discussions** related to system-level design. These are topics that have been proposed by faculty associated with the course based on past experience with student-team problem areas, including: technical block diagrams, process flow charts, system sizing and power budgets, power system safety, appropriate component selection, data sampling and error analysis. Discussions on engineering ethics, which analyze case studies and prompt learners to reflect on real engineering scenarios, are also presented.

Design Notebook:

The *SDP Guide to Project Framing and Design* was introduced as a framework to encourage a more holistic and entrepreneurial team mindset during the preliminary stages of the engineering design process. It contains tools and exercises adapted from IDEO's "Guide to Human Centered Design," Karl Smith's book "Teamwork and Project Management," Steve Blank's Business Model Canvas, and other literature [21,22,23] arranged to facilitate iterative cycles of divergent and convergent thinking as applied to project feasibility. It is divided into three sections:

1. Part I: Framing the Project
2. Part II: Project Proposal
3. Part III: Team Charter

Taken linearly, the first two sections of the design notebook are used by teams to formulate a preliminary model that can be proposed to the client, while the third section demonstrates the team's capacity to succeed. Learners' first interaction with the design notebook is in its application to the mock project during the heavily structured introduction phase to senior design. At this point, instructors assume students are more comfortable with prescriptive methods; indeed, mock project teams tend to utilize the notebook as a step by step guide to design. Reminiscent of the course structure as a whole, repetition of the framework during the less regimented transitional period allows teams the autonomy to adapt the tools as needed to create a comprehensive system model of their capstone project.

In order to exhibit feasibility and gain approval as a capstone project, teams must:

- Articulate the problem statement and demonstrate understanding by clearly identifying the need.
- Acquire new knowledge on the subject matter by managing the diversity of internet and professional literature sources
- Directly interact with the client and recognize potentially disparate perspectives
- Outline criteria for a successful project deliverable
- Context a proposed design through environmental, societal, economic, and technical lens
- Create implementation and assessment plans
- Assess potential short- and long-term impacts on communities

The team charter validates a team's ability and preparedness to tackle the proposed project. It is a "binding" document that governs team dynamics for the project's duration. Team members together reflect on past team experiences (the most recent being the mock project) to reinforce the fact that each member is united in a common effort, addressing what it means to relate to each other professionally. Effectively, the team charter frames different stages of team discord to facilitate recovery (through recognition and intervention) or ultimately provides conditions for termination. In it, teams must:

- Describe the requisite technical and managerial roles for project success
- Demonstrate team capability
- Assign areas of responsibility
- Define "respectful" team behavior
- Outline mediating steps in case conflict should arise
- Agree to abide by their outlined structure; each team member signs the document.

The fall quarter is organized to provide two design notebook submission cycles for each of the two projects, providing multiple opportunities for both formal and informal feedback.

Mock Project:

While our goal for the capstone course is to provide a culminating opportunity to *apply* previously acquired knowledge and skills – both technical and process, we recognize that many learners enter their senior year with limited experience in applied research, engineering design and project management. To help address this issue, we integrated a new key element: the mock project into the first six weeks of the course. This is an *actual* project with a *real* and identifiable client purposely selected to be on a topic outside of students' comfort zones, thus providing a realistic experience navigating ambiguity while compelling reliance on teammates. Ideally, students should begin to perceive the potential benefits from having multidisciplinary teammates with diverse backgrounds. Students work together in randomly assigned teams of four to apply the design notebook framework to a feasibility study with real-world implications, gaining experience in human-centered design while establishing a common "toolbox" of ideation techniques. These activities are highly scaffolded during class lectures to introduce, contextualize, or provide feedback in a group setting. Teams tackle the accompanying homework assignments outside of class, under pressure of weekly submission deadlines. All assignments submitted for the mock project are available for resubmission to demonstrate improvement in understanding.

The mock project grounds the lectures in something concrete, making them relevant *in real time* rather than abstract vacuous exercises. Learners are forced to work closely with unfamiliar team mates, likely from different departments, and thus experience the nascent benefits and challenges of teamwork while these topics are being discussed during lecture. For instance, during the lecture covering *why teams fail*, we noticed the common perception among students is that it will never happen to them and the lecture is cavalierly dismissed. These topics are now made pertinent as teams reflect on their own experiences and their own performance. Even if learners tend to treat the mock project as just another academic exercise (which is harder to do when accountable to an actual client), we find that the project-based approach helps learners to better internalize content.

As an example, last year's cohort worked on a solar-powered well project for a village in Cameroon. Students were given a design brief written by the local stakeholder and used this information to guide their design proposal. By using the design notebook framework, teams quickly realized that the information available within the design brief and online was insufficient for a successful and *sustainable* design; though teams were able to follow up with a Q&A session with the stakeholder via Skype, they still felt unprepared without further communication with the actual customer. An obvious constraint was economic in nature, but the focus on community forced teams out of their comfort zone to take a human-centered societal approach to their design – *why* did the previous implementations fail? How would you ensure that these mistakes were not repeated? How would you teach system maintenance to a community that does not have electricity? This project is an ideal example of a mock project, as success is not defined solely by educated attention to technical solutions but by its value and utility to the customer; indeed, this technology exists and is readily available in the United States.

Team Selection:

Weeks six and seven are dedicated to transition students into viable capstone teams. Team formation is a common sticking point in many capstone programs [17], SDP included. Arguably, instructor assignment of students into project teams is the easiest method to implement, yet risks member disinterest in the project topic, lack of diversity in needed skills, and perpetuates the role and mindset of Student-working-on-a-classroom-assignment. At the other extreme, allowing students complete freedom to decide which project to pursue – which is logistically difficult – does not guarantee team member and skill diversity. We take a more facilitated approach, still allowing for autonomy while holding learners to a professional standard when identifying areas of project responsibility.

At this point in the quarter, project pitches are ending and students focus not only on which project they would like to pursue, but also on its formulation; both the problem statement and team capability must be approved by the teaching team. Each student "applies" to their project of choice with a resume and cover letter through the SDP website, though they are not guaranteed a spot. The SDP website was introduced in 2012 into the course as a customized tool to help streamline this process and serves a vital function for centralized coordination. Individual learners can indicate their interest in single or multiple projects by signing up as "interested" under the project's website module, making their *Interests*, *Qualifications*, *Experience*, *Expertise*, and perhaps most importantly, their contact information viewable to potential teammates. Students use the website to schedule and attend team formation meetings where they not only learn more about the project(s), they also help to formulate its deliverable and thus dictate project direction. Once students have more or less settled into teams, they update their status to “joined” and seek instructor approval, usually around week eight. The project modules are then utilized by instructors to track team progress and host all project documentation through the end of the year.

In this way, teams are self-selected and self-aggregated; students must justify their presence to their peers and show that *together* they have the requisite skills and experience to achieve their personal goals within the context of the team’s overarching objectives. Interestingly, the corporate-sponsored projects are not always the first to fill even though the project is fully funded by a potential hiring entity; students are obviously drawn to projects that they pitched, but others value opportunities for learning or honing a new skill.

Hence, this phase of the capstone is still admittedly chaotic. Some students wait to be told what to do and require significant handholding to navigate the process. As the end of the quarter draws nearer, there are always a few students scrambling to join a team. Furthermore, nascent teams struggle to fully define their project proposal for instructor approval, now with no deadlines other than “the end of the quarter.” This marks a notable shift toward team accountability. Learner reliance on the design notebook framework combined with focused but informal instructor interaction eases the project framing process, enabling teams to flesh out a problem statement for an identified need – either one proposed to them or one that they themselves have identified.

Fall Deliverables and Learning Outcomes

The objective of the fall quarter is to position student teams with the tools required for group efficacy in the coming quarters. The primary deliverable is the design notebook, a written record of the project framing process, completed first for the mock project and then again for their capstone team. The design notebook is simply as assessment tool, evidence that a team has achieved the intended outcomes and is poised to begin the next phase of the engineering design process. In addition to the items mentioned earlier in this document, teams submit a project budget, list of lab and equipment requests, as well as a Gantt chart. As can be seen in Figure 1, individual assignments are also spread throughout the quarter, usually as short essays prompting students to reflect on different aspects of the team experience. The table below summarizes a list of assignments and their intended learning outcomes:

Table 1: Description of fall assignments and associated learning outcomes

Individual Activities	**Learning Outcomes:** written communication
IQEE: Interests, Qualifications, Experience, Expertise template	Self-Reflection and personal skills assessment
Project Incubation: Essay that addresses incubation prompts	Project framing that demonstrates understanding of the client needs; generate problem statements
Cover Letter and Resume: Application to mock project	Self-Reflection, skills assessment and the ability to identify project requirements
Mock Team Reflection: An exercise in professional level writing candidly reviewing their understanding of the Mock Team.	An appreciation of the purpose and value of team-based engineering projects.

Cover Letter and Resume: Application to Capstone project	Self-Reflection, skills assessment and the ability to identify project requirements
Case study reflection	Engineering Ethics
Team Activities	**Learning Outcomes:** Communication, interpersonal skills, teamwork
Block Diagram: Draft block diagram with reasoning and justification in essay form	Understand the role of system level thinking expressed as a block diagram
Annotated Bibliography: Independent research	Demonstrate ability to source and learn new knowledge and understanding
Criteria Matrix and Pugh Chart: Apply these tools to first identify metrics for project success and then in decision-making	Context solutions by disparate perspectives and formulate a framework for project success with logical indicators; trade-off assessment
Flow Chart with Impact Assessment: Chronological project flow with milestones	Project planning and post-implementation assessment of outcomes across sectors
Project Framing: Apply methods learned from mock project as a template	Use tools to generate a holistic understanding with knowledge of contemporary issues;
Project Proposal: Apply methods learned from mock project as a template	Generate viable project outcomes demonstrating team ingenuity. Client negotiation
Team Charter: contract depicting mutual norms and values that team members must adhere to that includes social and technical dimensions of responsibility	Understand why a well-articulated social structure is necessary for a team's success. Articulate areas of exclusive responsibility

Industry-Style Management

During the winter and spring quarters, the course adopts an industry-oriented approach to project management using a hierarchical structure emphasizing autonomous team and individual responsibility. Capstone teams are provided dedicated equipment and laboratory space. There is no set course schedule; weekly management meetings are scheduled depending on instructor and student availability while teams are responsible for establishing internal meeting times and group work schedules, in keeping with the guidelines outlined in the charter. Teams are given minimal guidelines during this phase, primarily to inculcate individual responsibility and shift the burden of progressive assignments from the teaching team to the team itself.

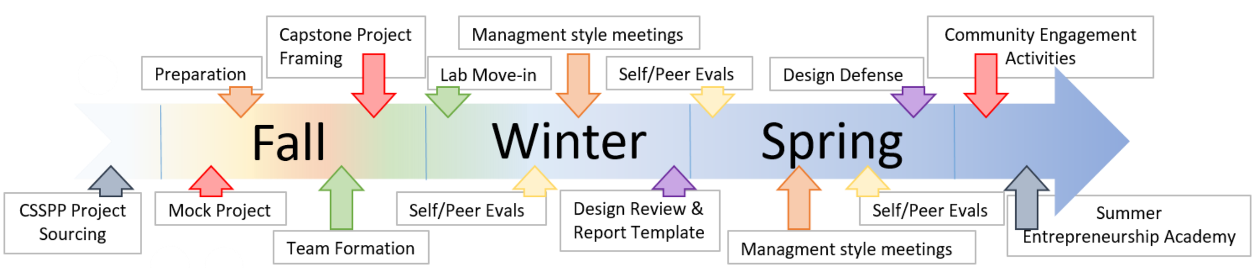

Figure 2: Graphic depicting the major milestones and course progression over the three quarter sequence

Management Meetings:

Each team meets with an instructor at a designated time each week for an hour-long executive summary meeting meant to apprise their "project manager" i.e. the instructor and TA (the de-facto teaching team), of team progress. Unlike the instructor-team meetings in the fall, the agenda is set by the team and students lead the discussions, rotating each week to a different team member. Teams must cover a minimum of three items: high-level succinct summaries of last week's progress, any challenges or insights gained, and next week's action items where intentions are expressed in tangibly achievable terms. Individual progress is tracked as weekly reports that are amalgamated into a group-level status update for the project's manager, mirroring the meeting format. This reporting structure emphasizes a top-down, rather than bottom-up construction of the week's progress, which is typically quite new to students who otherwise focus on individual chronologically enumerated technical minutiae lacking team or system contexts.

Other than this, teams determine their own templates, management style, and general team interaction; they act as employees justifying their work as professionals to management professionals assigned to supervise their work. The instructor's role becomes one of senior supervisory management, primarily providing feedback and suggestions to help teams manage themselves, keep focused, and maintain productive progress. Thus, the actual duration of the weekly meetings not only depends on team size, but also their level of preparation. Teams additionally maintain a biweekly or monthly meeting with their client, either in person or via teleconference where they apply a similar meeting style. Teams are required to keep professional minutes of these meetings.

Self and Peer Evaluations:

Bi-quarterly team self and peer evaluations is an example of an integral course exercise that was directly adapted from industry practice beginning in 2005 by a member of the teaching team, Lecturer Cyrus Bazeghi. These forms were originally created in Microsoft Visio, printed and distributed to students. Later, they became electronic and are now part of the SDP website, accessible under the project modules. Team-members reflect on the interpersonal dynamics of their team in a private form with results available only to the teaching team. Not only do they assess their teammates' "performance and contributions to the project" but also metacognate on their own. After the evaluation period, teams hold an additional team meeting specifically to candidly and honestly discuss any issues, both positive and negative, that surfaced during evaluations. This is a mandatory activity that many students stridently try to ignore. Instructors review this meeting's minutes to ensure teams express and manage any identified issues.

This exercise provides instructors valuable insight into a team's dynamics. In many cases, the assessments reaffirm what is already suspected or known, however, there are always a few surprises. Furthermore, these assessments help to gauge individual student progress, revealing improvement or when learners fall behind. As the self and peer evaluations are used in grading, some teams unfortunately decide to give each other unwarranted outstanding reviews while others are overly critical; instructors must subjectively weigh their utility in student and team assessments. The real value lies in the practice of self-assessment and team metacognition, which has been shown to accelerate team cohesion and enhance performance [24].

Social Hour:

By the winter quarter, students are fully segregated into teams in allocated workspaces. Unless they are sharing a large lab space, communication between teams is minimal even though many teams share similar struggles, research and utilize the same parts and thus run into the comparable difficulties upon implementation. In order to address this, we recently implemented a bi-quarterly social hour with snacks and drinks provided. We observe that team-members use this time to mingle, unwind, compare capstone experiences, and gauge their progress against other teams. Though limited feedback has been obtained, students respond well to the opportunity for interaction. It is not clear if we have achieved our objective of having teams realize that everyone is more-or-less facing the same obstacles; we plan to employ mediated discussions during the next capstone cycle in an attempt to highlight common challenges.

Winter Deliverables and Learning Outcomes

During the winter quarter, teams coalesce into professional social units that persist for the remainder of the course. Typically, several weeks are needed for students to understand the larger management style and adopt the professional format we are instructing them to learn. High-performing teams quickly master this and begin to perceive that success is not possible without their peers, affecting more streamlined collaboration. Supporting one another as a professional and ethical duty becomes an immiscible ingredient of success, superseding their habitual and comfortable narcissistic view of inter-peer relationships. Anthropologically, this constitutes a rite of passage from callow student to nascent professional capable of entering the industrial workforce. See Table 2 for an overview of the primary deliverables for winter quarter and associated learning outcomes.

At the end of fall, teams projected their own deliverables for winter quarter and now must settle on what they may tangibly provide based on what sort of progress has been made. This forms the basis of their grade and includes the matter of quality progressive documentation in the form of a template for the final written report, typically much neglected up to this point and very unpopular with students.

Table 2: Winter quarter deliverables and associated outcomes

Deliverables	**Learning Outcomes:** Navigating ambiguity
Individual/Group Reports: Summarize progress from a top-down management-oriented perspective	Professional verbal and written communication; Leadership; Business and management skills; Improved sense of professionalism
Weekly Management Meetings: Team-lead progress meeting	Learn to comport themselves as professionals, learning to express themselves as professionals and competently assess individual and group performances
Self and Peer Evaluations: Periodic metacognitive assessments	Understand the ethical duty of commitment to the team and each member's own place in it.
Design Notebook Check: Professional engineering log	Learn prevailing industrial practice of keeping professional engineering notebooks.
Draft Report & Template This forms the basis for later final documentation	Provides written evidence of analytical skill, ability to apply and adapt engineering methods, interpret data

Project Check-off/Presentation A cadence point providing a means to grade technical progress and assess communication skills.	Provides concrete evidence of analytical skill, ability to apply and adapt engineering methods, interpret data. Understanding of system level design.

End of the Year

The final quarter is ideally devoted to system integration, preparation of professional quality documentation and participation in a variety of venues emphasizing academic, entrepreneurial and industrial avenues to success.

Technical Communication:

Teams enter spring quarter at varying levels of team cohesion and project completion. Many have had to rework their Gantt charts to accurately reflect their more honed ability to organize and complete tasks, resulting in either downgraded project deliverables or stretch goals now incorporated into the main scope of work. Regardless, all teams are responsible for the design, fabrication, and at least preliminary testing of a physical prototype by the end of spring quarter. Teams demonstrate and are assessed on their effectiveness in the engineering design process through multiple venues, both written and oral. Accompanying documentation, in the form of a report and product manuals or app notes, must be professionally composed and comprehensive. Teams also undergo an hour-long "design defense" in front of a technical committee, where they present their prototyped solution to the committee, clients and their peers in a format loosely based on a thesis defense. Each team member is required to present and are assessed in terms of their design decisions, evaluations of trade-offs, and technical integration proficiency, in addition to professionalism.

Community Engagement:

As mentioned earlier in the paper, capstone projects and team composition are only approved if teams identify and interact with a specified customer base that would benefit from project outcomes. For some projects, this step is straightforward; the need expressed in projects pitched by corporate-sponsors and academic stakeholders comes neatly defined with an identified client. Other projects, such as those pitched by community partners, NGOs, and the students themselves, are usually in service of an external population where a need has been loosely recognized (e.g. the community in the mock project had a lack of accessible water) but there is increased burden on the teams to fully characterize the opportunity for value creation to be actionable by the team. In both these cases, teams still must fully flesh out a problem statement, negotiate with the client, be able to articulate constraints, and context solutions in terms of potential societal impacts.

This process is in support of the course's targeted learning outcomes: to engage and communicate with diverse stakeholders by working across disciplines and sectors and propose sustainable solutions to societal challenges. The end-of-the-year community engagement activities provide the teams the opportunity to *engage* with diverse audiences and *demonstrate* their understanding of how their capstone project addresses a need within communities of practice. Due to the sheer numbers of teams and the disparate natures of the projects, SDP at UCSC hosts three community engagement events to reflect the three project tracks (presented here in order of introduction to the course, not in sequential order), each with their own associated preparation activities:

- **Corporate-Sponsored Senior Projects Day**: Teams present a condensed (8-10 minute) presentation to a predominantly **industry**-oriented audience comprised of engineers associated with the companies that sponsored projects. After the presentations, lunch is served concurrently with a poster session where teams may optionally provide a project demonstration. Teams use this event as an opportunity to network among professionals and many do gain employment or internships as a result of the event.
- **Senior Design Conference**: Teams present a condensed (8-10 minute) presentation in parallel, themed tracks in an event that mimics an **academic** conference. Audience members, comprised of interested research faculty, stakeholders, and the students' friends and families, are able to move between tracks and learn more about the different capstone projects. After the presentations, lunch is served concurrently with a poster session, optional project demonstration, and tours of teams' lab spaces. The senior design conference is the last event of the year, held on or the day before commencement.
- **IDEA Hub's Pitch for Social and Creative Enterprise:** This off campus event is hosted in conjunction with our Center for Innovation and Entrepreneurial Development and the Santa Cruz New Tech Meetup in the community. Teams whose projects fit the criteria of "social and creative **enterprise**" enter a university-wide competition where finalists are selected to pitch their ideas to a panel of tech experts, investors, business founders, and potential mentors. In the first half of the event, the finalists compete for cash prizes ($500 – $3,000 for first place) and material support to continue their innovations beyond the academic year, including entrance to our summer entrepreneurship academy. During the second half of the event, all teams showcase their projects alongside local businesses during Santa Cruz's New Tech Meetup's annual job fair. Refreshments and hors d'oeuvres are served throughout the night.

Spring Deliverables and Learning Outcomes

Of the three events, capstone teams respond most positively and seem to derive the most value from the Pitch for Social and Creative Entrepreneurship, stating that they "*want to showcase our design as [it is] potentially commercializable*" and want to "*show what we are able to do using technology*" and "*see what the world thinks of us*." These statements support achievement of professional efficacy, a primary learning outcome for the course. By presenting alongside industry professionals and potentially winning significant cash prizes, this culminating event facilitates the transition to the entrepreneurial mindset; supporting the notion that learners are capable of more than what is required as an academic exercise, but may realize "*real world impact*."

Table 3: End of the year deliverables and associated learning outcomes

Deliverables (all of the above plus)	Learning Outcomes: Professional Efficacy
Final Report + associated documentation	Provides written evidence of professional analytical skill, ability to apply and adapt engineering tools, interpret data
Design Defense: hour long technical presentation with panel of experts	Ability as a team to professionally articulate a coherent picture of the engineering design of their project
Poster Presentation	Demonstrate visual communication to academic and general audiences
Community Engagement Presentation	Demonstrate professional verbal communication to diverse audiences, contexted by the impact of engineering solution
Final Deliverable: a functional prototype	Evidence of technical and systems level understanding and ability to translate theory into practice; group efficacy

Part 2: Discussion of Emergent Themes

The Baskin School of Engineering (BSOE) at the University of California, Santa Cruz is a fairly young initiative, officially founded as an engineering school in 1997. However, the effort to bring engineering to UCSC began further back in 1984 as two new departments, each with their own undergraduate program tracks: Bachelor of Science in Computer Engineering (CE) and Bachelor of Arts in Computer Science (CS). By the time the first class of its students graduated in 1988, the Computer Engineering program was ABET accredited and these students received an accredited Computer Engineering degree. As part of this effort, CE offered a mixed-department, one quarter capstone course titled "Advanced Microprocessor System Design".

This discussion reflects on the last twenty years of the engineering capstone course from the perspective of instructors that oversaw significant changes, as well as the minor curricular adjustments needed to develop the real-world experience the course now provides while coping with the expansion of BSOE and its growing student body. This retrospective is valuable for several reasons. It presents lessons learned and reasoning behind pedagogical scaffolding that bolsters leaners' ability to navigate ambiguity and provide real-world impact, We also identify scalability as a real problem; this includes the need for qualified faculty and teaching assistants capable of mentoring the broad topics required for successful team-based and entrepreneurially-minded engineering design. A successful capstone project sequence must address all of these.

Course Development

Over this time, the course expanded from the one quarter, 5-unit capstone mentioned above into a 15 unit, three quarter sequence absorbing what used to be separate courses in engineering ethics and technical writing (disciplinary communications). The escalation of instructor effort, resources allocated in addition to student time, is in response to the teaching team's increasingly refined definition of "authentic" and "professional" engineering practice, which fundamentally shaped the learner experience over the years. Participating faculty consisted of several dedicated enduring tenured faculty from EE and CE with significant experience beyond academia and several continuing lecturers from these and other engineering departments. Some lecturers in particular brought additional and concurrent industrial experience that contributed to a unique idiosyncratic mix of skills. Often TAs also had professional experience, most frequently as interns in industry.

Major Milestones

The original capstone class afforded students the opportunity to apply skills acquired in prior coursework and accomplished this goal within a simple project-based learning structure. Learners worked individually on a single, predetermined project; for many years this was the IEEE sponsored Micromouse Competition. The purpose was to consolidate and demonstrate engineering acumen while being introduced to the full cycle of engineering design. At the time, this course was learners' first true interaction with open-ended project work; students experientially progressed through iterative design to complete a prototype. This simplified approach to project-based learning made course logistics and student assessment more approachable than with team-based PBL, but missed out on the subtleties associated with collaboration, ownership and other social processes predictive of innovation and efficacy [11,25].

The introduction of the ABET EC2000 criteria prompted the first significant transformation of the capstone experience to better address these new student outcomes. Coincidentally, the newly established Electrical Engineering Department was also formalizing a culminating design experience for their undergraduates. The two quarter capstone Hardware Design (EE) and the CE course were merged (informally, at first) to form a two quarter, 12 unit sequence: "Engineering Design Project," where the first quarter was used to teach project management and teamwork while formulating viable projects so the second quarter could be dedicated to project design. Each department assigned one instructor to teach the full sequence and class sizes were kept small by running two cycles each academic year. The earlier practice closely associated with prescriptive learning, where students were assigned to project teams by faculty, was changed. Teams in the new two-quarter sequence assembled themselves by self-selecting and self-aggregating, a process run by the students. Final approval of team size, division of labor, and composition necessitated that students justify their roles to faculty.

This structure prompted what would become an organic progression of multidisciplinary inclusion within the course. Instructors formed an informal "Teaching Team", the dynamics of which were reflected in the now self-aggregated student design teams. Instructors not only represented different departments but had diverse backgrounds stemming from years working in different sectors; thus, providing first-hand knowledge of current industrial practice. Each contributed their own insight into professional engineering practice, which served to develop and consolidate the "industry-oriented management model" over the next few years. At this point, projects were predominantly self-conceived by students or in some cases faculty, but were required to have applications in the real world for an identified customer base.

The shift to a three quarter sequence in 2012, first for 12 units of quarter credit and then for 15 units of quarter credit beginning in 2017, marked Senior Design as being a rite of passage for the UCSC engineering undergraduate. This expansion into a project-based course spanning an entire academic year made room for more sophisticated projects and the potential for real impact; the change was received enthusiastically by the students. All projects now required some level of interaction with an identified client, not just corporate-sponsored projects (which launched in 2012). The goal for all capstone teams – one that was becoming more explicit – is to create real value within an identified community of practice. Accordingly, instructors recognized the need to better prepare learners by enhancing the entrepreneurial mindset needed for improved project efficacy; without consistent prior preparation, a two quarter sequence did not afford multi-departmental teams this opportunity. Figure 3 depicts the major changes in the senior design capstone course from 1998 to present.

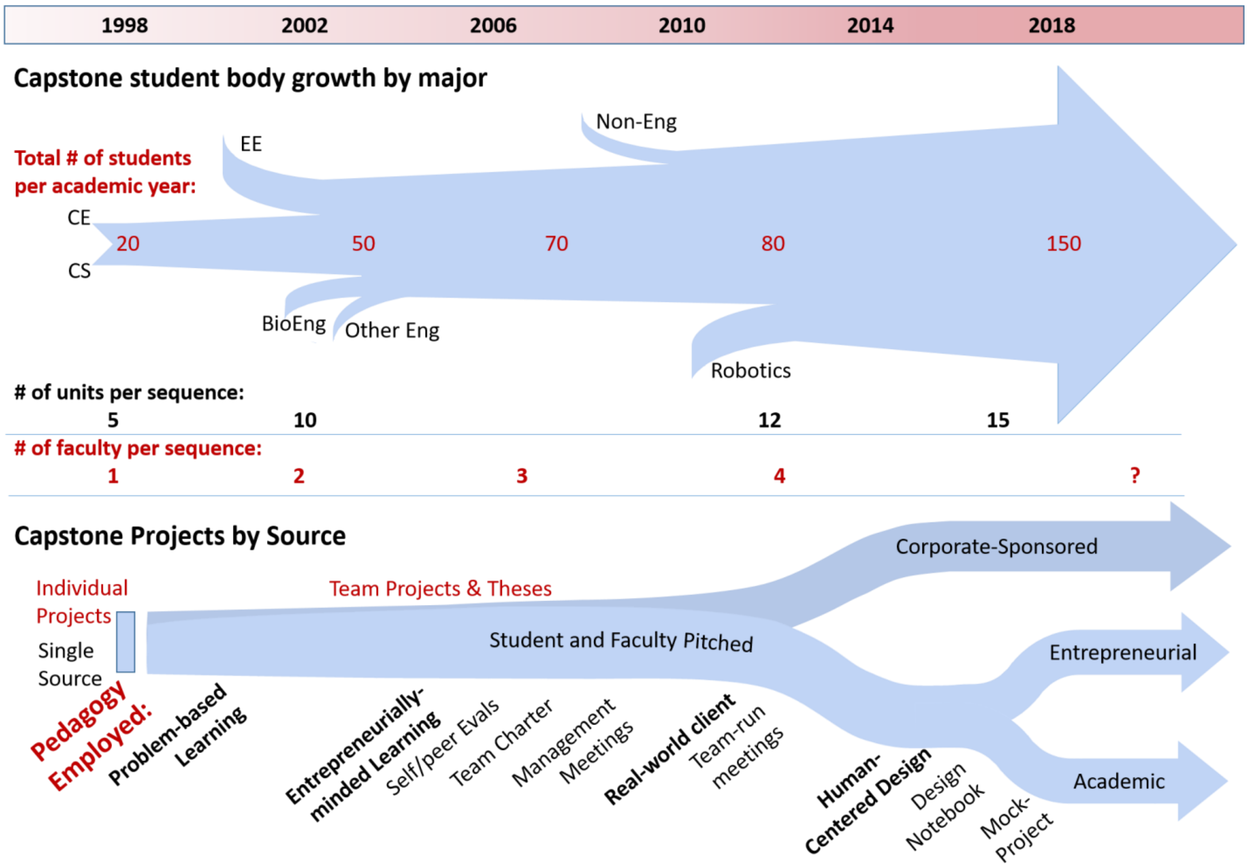

Figure 3: Summative timeline depicting the major changes in the capstone course over twenty years

Logistics

The Senior Design Capstone Course is a demanding program that asks more of both leaners and instructors than most other classroom experiences. The investment goes beyond expending extra time and resources on difficult program structure, project sourcing, and learner assessment, which are characteristic of PBL and EML in contrast with didactic classroom methods. The capstone course is about personal growth, achievement and discovering what it means to be a professional engineer. There is an emotional investment made on the part of both students and instructors who mentor teams' growth over a full academic year – and for many it is worth it. Exit interviews reveal that the capstone course is often cited by graduating seniors as pivotal in preparing them for industrial employment, while also described as their "most enjoyable undergraduate experience."

Providing this experience requires the engineering school to make an explicit policy decision to support learners, instructors, and allocate the extensive administrative backing that engenders an environment conducive to authentic engineering design. While historically each department assigned instructors and resources to the course, as needed, a more formalized model is needed in order to scale and still maintain student outcomes.

The Numbers: The 2012 decision to expand the capstone course over three, 5-unit quarters created strain on the departments and BSOE as a whole, as the course now required significantly more resources and logistical support. Moreover, this transformation coincided with a dramatic uptick in the engineering undergraduate student body:

- Current capstone enrollment ~150 students
- Current number of students per instructor: average 36 (up from 18 before 2012)
- Current number of students per project: average 5.6; [2, 10]; (up from 4.4 before 2012)
- Current number of teams per instructor: average 6.7
- Average increase in course enrollment per year since 2012: ~20%
- Average number of majors represented each year since 2012: 7

According to the 2015 Capstone Design Survey conducted by Howe et. al., [26] we see that some of these numbers are strikingly high when compared to the national averages. The BSOE Program's average number of capstone students per sequence and, accordingly, the number of distinct projects per sequence are as large or larger than those in 90% of survey respondents. Similarly, the average number of students per capstone design team is beginning to deviate from the numbers represented in the survey, where the stark majority of respondents reported an average team size of 3-5 students.

Faculty Load Model: Instructors spend their time predominantly with teams in weekly management meetings, each targeted to last an hour – if the team is prepared and manage the meetings efficiently. Generally, these take anywhere from 45 minutes to 2 hours per team as teams learn to present their work professionally. Outside of these meetings, instructors review their teams' reports and documentation, serve as technical mentors, interface with clients, and organize and attend the end-of-the year functions. We estimate that a well-run team requires an average of 2.5 hours of weekly support. For 5 quarter-units of teaching credit, we advise **a limit of 28 students or 7 teams per instructor**; whichever is fewer, to allow for the mentorship needed to facilitate team cohesion and professional management.

As the program became more established, teaching assistants were introduced into the capstone course as full members of the teaching team. Each instructor is assigned a TA for winter and spring quarters, who operates as an intermediary between instructors and teams. As graduate students who have gone through this or similar capstone programs, they engender a more casual and approachable dynamic. In practice, TAs are instrumental to the program model; they help teams implement instructions, identify latent issues within teams, and advise instructors on their resolution.

Student Load Model: The Senior Design Program nominally requires a total of 450 hours of work from each student. In reality, the time and effort teams put into a project will vary dramatically depending on several variables: project requirements, team preparedness, familiarity with engineering tools, individual academic load, planning ability and time management. Teams state their minimum weekly workload in their charters: typically 15-20 hours per week. Those that maintain this pacing with clearly defined goals, milestones and established divisions of labor make significant progress earlier in the year. In many instances, however, teams' workloads vacillate, usually to the detriment of project outcomes. Many view the end of the program as the distant future and put in minimal effort in the winter quarter, only to "exponentially push" come spring. Conversely, previously engaged teams may suffer from "spring quarter burnout." In the latter case, teams complete the first phase of design at the component level but are reticent to tackle systems integration and documentation. As a result, the teaching team has been placing increasing emphasis on the importance and difficulties associated with systems-level design; we have developed several lectures in the first quarter dealing with the general topic of engineering design and system-level thinking. Unfortunately, we have yet to develop the best experiential means, beyond that of direct mentoring, to convey the message so that learners may be better prepared.

Logistical Support Load Model: All teams are allocated dedicated laboratory space, with a workbench, test equipment and 24-hour access. Before gaining access to the lab, teams are required to complete EH&S (Environmental Health and Safety) training at a level appropriate for the project and the equipment they will be using, e.g. laser cutter or high voltage safety training. Additionally, teams can request workstations, software, tools and other equipment needs specific to their project as articulated in the design notebook. Baskin Engineering Lab Support (BELS) handles all course-related logistical support. For SDP that includes scheduling, student access, equipment tracking, room preparation, poster printing, and more; all activities are coordinated with instructors. BELS also runs a supply shop stocked with electronic components, 3D printing filament, and other course-related consumables. Come winter quarter, BELS takes on a dedicated student hire to accommodate the increased resource demand.

Funding Model: Senior Design is an expensive course that requires significant coordination and resources and a relatively high faculty to student ratio. External sponsorship raised by the Corporate-Sponsored Projects Program supports program growth, allowing for dynamic changes to be implemented more rapidly. Sponsored project fees are a set cost, though two tiers are available depending on the economic size of the sponsor. Currently, corporate-sponsorship funds are used to cover the additional BELS hire, additional laboratory equipment, end of the year events and teams' social hour, salaries for some instructors and TAs, in addition to sponsoring the industry projects. Projects that are not externally sponsored are funded by the teams with the explicit expectation that students are on the hook for project materials costs on par with the cost of a course textbook. Consumables and 3D printing "purchases" from BELS are covered as part of a $10 student quarterly course fee. Beyond this, faculty support students in applying for project grants through their colleges, UCSC's Center for Innovation and Entrepreneurial Development, CITRIS grants, campus sustainability funds, crowdfunding campaigns, as well as off-campus granting entities. The majority of teams receive one or more grant award.

Focus on Efficacy and Innovation

Preparing the next generation of engineering professionals for today's challenges requires a pedagogy that reflects complex themes and fosters creativity, engagement and the entrepreneurial mindset required for innovation to flourish. The engineering capstone has truly become a rite of passage away from the necessary initial isolation of highly structured formative academic frameworks, enabling learners to overcome barriers typically experienced in later professional practice within a facilitated and transitional environment. Even learners that have industry experience in the past gain from the program; they take on more complex and open-ended projects, pursue entrepreneurial endeavors, and/or take on leadership positions within team, driving the design forward. Successful teams together learn to adopt a holistic approach, solving problems as a complex system involving a diverse set of stakeholders. Thus, we find that movement towards an entrepreneurially-minded pedagogy with real world application and accountability ultimately results in enhanced group- and self-efficacy, a requisite construct of innovative practice [11,25]. Based on senior exit interviews, instructor, TA, ABET and client feedback from as far back as 2003, certain course activities and key features contribute most strongly to these outcomes.

> "*The most enjoyable part [of my undergraduate experience] was my senior design project because I got to apply almost everything I learned in previous laboratories into a project that would have real world impact. Even though there were many late nights in lab, it felt good to work on a project that has more meaning than just another homework assignment*."

Design Thinking as an Engineering Process

Navigating Ambiguity: Subsequent changes and expansion of the Senior Design Program correlate significant ***challenges*** for learners with activities provided within the framework of the design notebook, namely those associated with the creative process of divergent and convergent thinking that accompanies uncertainty and ambiguity. Initial interaction with this process is often met with trepidation and skepticism; on the one hand learners express concern that they are unable to converge on "the right decision," inducing decision paralysis. On the other hand, student feedback early in the year suggest that these activities are "*simply common sense*" and that learners "*didn't put in much effort*" into preliminary assignments. We postulate this is due to the lack of buy-in which was not unexpected. As teams progress during the winter quarter, however, we observe members using these tools in adaptive ways, usually to move the decision making process forward when faced with uncertainty. The senior design program provides many supported opportunities to "practice and fail" and ultimately hone design skills by exposing learners to design thinking strategies, beyond the linear and predictive single-problem solution.

Team Selection and Project Ownership: Students self-aggregate into teams following a messy selection process. They are not only responsible for their ***choice*** in selecting a project that appeals to their own needs and identifying their own area(s) of responsibility, but also begin shaping the project outcome at this early stage. Students are responsible for the formation of the team as an entity, ensuring that it is capable of performing the requisite tasks at a time where there is no clear project leader. To do this successfully requires communication, project framing, skills assessment, and ultimately tacit leadership. The resultant outcome is ownership over the project and project tasks; students recognize that decisions made by an individual or as a team have repercussions that affect the potential success of the project. When asked during exit interviews to identify the most enjoyable part of their undergraduate education, one student responded:

> "*Pursuing my startup idea through the use of senior design. Participating in a large project that I've always had interest in and ties directly into my engineering coursework was and still is a fulfilling experience*."

Management Meeting Model: Adopting industry-style management that is ultimately highlighted by team-run, instructor-student meetings forces students to justify their work ***as professionals***. Effective use of this practice requires a fundamental shift in mindset, from causal and prescriptive reasoning to effectual thinking. This is the ideal scenario, where teams are functioning synergistically. The time it takes to achieve streamlined collaboration varies depending on size, members' personality, backgrounds and motivations. Not only is the management role new for students, the instructor's role is new for faculty who must learn and understand the social dynamics of supervising team-oriented engineering design that deviates from the lecture-listen format and traditional micro-managed incremental assignments. Unlike these traditional academic exercises, incorporating activities directly adapted from industry practice better supports group efficacy: formulation of a project proposal and the accompanying client negotiations, self/peer evaluations, and investor presentations during the end-of-the-year community engagement. As one external evaluator put it: "*The capstone design course has a good test of professional and ethical responsibility through mutual peer reviews of all students in each design team*." Together, these activities are designed to reinforce student's potential for impact beyond the confines of the academic setting. Teams are encouraged to apply for project funding and support, submit to conferences, enroll in the summer entrepreneurship academy, or in other ways represent the university, encouraging self-efficacy and confidence in one's own professional ability.

Project Sourcing: Projects pitched during the fall quarter of senior design originate from a prospective client or are student-conceived. Regardless, they must represent real-world value, either directly for the client or another identified customer base. As a result, teams feel *accountable* to an external stakeholder, one that is invested in project outcomes. Interaction with stakeholders helps to formulate project success, articulate goals and ultimately provide structure for teams during the creative process, though it also increases pressure and potentially adds stress that some teams have difficulty coping with. Indeed, the introduction of the corporate-sponsored program initiated a fundamental change in course structure as there is now an implicit assumption of project success. We find that this sense of accountability is operational in driving a collaborative solution forward, though teams must be equally invested in the project. As such, not all project pitched to the class make it through the fall quarter with a team, even the fully funded corporate-sponsored projects.

The three emergent program themes reflect the inherently diverse natures of the different projects, each with their own associated benefits and challenges.

- **Corporate-sponsored projects** are usually accompanied by explicit goals and constraints, and potentially could result in a job opportunity upon graduation. In fact, many proposed corporate-sponsored projects originate from SDP alumni working in industry. Industry sponsors make a sizable investment into the program and thus own any IP, resulting in increased pressure on both the team and faculty to complete the project. Thus far, this program has been successful in providing value; many corporate sponsors view capstone teams as an investment and repeat their engagement with program over multiple years. Not all corporate-sponsored projects are sought after by the students, though they do eventually find a team. Some example projects include:
    - Corning *60 GHz Glass Waveguide*: Develop a demonstration of the use of glass waveguides to provide connections at 60GHz or higher. (2013)
    - Plantronics *DECT Radio Tester Replacement Project* (2015)

  - Mercedes-Benz *Acoustic Source Location by Time Delay Estimation*: Develop a beamformer embedded system for directional spatial filtering from an in-car acoustic array. (2016)
  - Amazon Lab 126 *RFID Dash:* Demonstrate the capabilities of the RFID antenna array as devices pass by on a conveyor belt. (2016)
- **Faculty sponsored projects** tend to be the most comfortable; the project is well-defined, the client is never difficult to seek out in case of questions, and students are most familiar operating in an academic environment. Projects tend to come out of research faculty labs, but also includes collaborations with other project-based courses and service learning programs with off-campus implications. As such, IP is owned by the university and faculty involved, though this delineation becomes less clear if students invest their own money. This track best situates students for graduate school, though students have received job offers directly as a result of their faculty-sponsored project, perhaps in part due to the outcomes achieved in a more familiar work environment. Students select these projects based on personal interest in the subject or skills required; on average 70% continue to winter quarter with a capstone team. Some example projects include:
  - Sri Kurniawan *Computer Aided Stroke Assessment Therapy using Virtual Reality*: Design a portable immersive 3D system that accurately records and transmit user data for assessment and therapy of people with disabilities performing motor tasks. (2013)
  - Ali Yanik *Smart Phone Fluorescence Microscope:* Design a low-cost platform for point of care detection and diagnosis of disease. (2016)
  - Don Wiberg *Help Alert–Home Assistance Button*. Design of an affordable health alert system for senior citizens (2016).
- **Student-conceived projects** tend to be the most diverse in nature and require significant effort to define into an appropriate project for a senior design team. Teams must find stakeholders that would be willing to communicate with them, be interviewed, and complete surveys, in order to situate the project in reality. In addition, teams must locate funding or financially sponsor the project. As a result, less than half of the projects pitched during fall quarter are approved and attract a team. Teams electing to take on student-conceived projects tend to get out of it what they put in: exceptional teams have won the pitch competition, gained investor interest and some have gone on to launch start-ups, as IP is completely owned by the students. Projects for external competitions also fall under this category, as these are generally student-driven. Some example projects include:
  - *History of Lebanon:* Design, construct, and test a functional prototype of a useful history archive to remedy Lebanon's lack of any formally recognized history after 1946. (2010)
  - *VisorNav:* The design and fabrication of a simple and distraction free navigation system for cyclists using a visor mount. (2015)
  - *Barbell Trainer:* Design of a device which helps people improve their squat, bench, and deadlift technique. (2016)

- *OVAC Autonomous Ocean-Floor Sediment Collection Device*: Improve on the current industry standard with a simple to use underwater autonomous drone. (2016)
- *HUMMINGBIRD*: Vocal control for electronic musical instruments. (2016)

Since the introduction of corporate-sponsored projects in 2012, SDP has seen roughly an equal distribution of approved project-teams across the three tracks, with slightly higher preference for student-conceived project. These figures are contrary to the national average, where universities tend to favor projects sourced from industry or faculty research, though percentage of student/entrepreneurial projects is on the rise [1,26]. As can be seen in Table 4, the distribution does not hold when analyzing number of teams involved with the different community engagement events, controlled for external department participation. These results may simply reflect the exclusivity of the competition or a shift in team perception as their engineering designs progress.

Table 4: Distribution of project themes by project source compared with team-selected participation in the end of the year community engagement events. Both the Pitch for Social and Creative Innovation and Corporate-sponsored Project Day is restricted to merit-based entries. Note that total participation in the events is greater than 100% as a few teams elect to present in more than one event at the end of the year.

	Corporate-sponsored	**Faculty Sponsored**	**Student-Conceived**
Average Distribution:	29%	30%	41%
Community Engagement Event	**Corporate-sponsored Project Day**	**Senior Design Conference**	**Pitch for Social and Creative Innovation**
Participation:	38%	44%	32%

Multidisciplinary Inclusion

The multidisciplinary subtheme prevalent within the senior design program began with a cogent argument by instructors to remove departmental silos and combine the EE and CE capstones, made possible by the then small numbers of graduating seniors. However, the benefits and challenges of multidisciplinary teaming were initially minimal until projects became more complex and had real-world implications. Projects based in authentic design, such as many of the above project examples as well as the example mock project, consequently demand mixed and diverse skills. This is another area where diversity among instructors proves beneficial; they can directly speak to the importance of communication, breadth in knowledge and skill, and the ability to work with perspectives different from one's own. Thus, the pervasiveness of multidisciplinary inclusion among both the teaching team and student body correlated with the strengthening objectives of program themes.

Cooperation and collaboration across sectors decrease homogeneity in design thinking, leading to holistic understanding and a larger resource pool from which to innovate. Or as IDEO put it: "To maintain creativity, we always work in teams [22]."As the UCSC's School of Engineering matured, the Senior Design teams began incorporating students from the new majors. Currently, each SDP cycle sees regular participation from Robotics, Computer Science, and Bioinformatics-Bioengineering and less frequently Network and Digital Technology, Applied Math, Physics and Chemistry. Learners' response overall has been overwhelmingly positive, one student put it:

> "*The journey in working with a team in trying to reach a common goal was an incredibly satisfying experience. Learning to work with others and being able to set worthwhile aspirations are two definite things I have taken away from my time here*."

However, truly holistic design necessitates diversity in design thinking. Solutions must not only be technically feasible, but in many cases be economically, environmentally and socially viable as well. Over the years, many SDP teams have tackled projects with clients hailing from different disciplines and sectors, and almost all of these presented challenges in communication. Teams had to learn to translate client objectives into technical specifications and then ensure understanding of their proposal and eventually the prototype. It was not until 2010 that the teaching team allowed for non-engineering students to be integrated into senior design teams. The first instance was a success: a master's student from Digital Arts and New Media worked with a team on an electronic platform for her master's project. She was both client and team member, and all students were motivated to complete the project. Unfortunately, this is not the typical experience. Disparate importance placed on communication, work expectations, and the value of diversity does not allow for team cohesion. Thus far, the capstone teams spanning different divisions tend to fail to achieve their goals, though ultimately team members come to view each member's expertise as an asset.

Both students and instructors seek to integrate Engineers Without Borders and other projects based in student service that leverage diverse knowledge and skillsets. One option is to address barriers to interdisciplinary project before reaching the capstone course. To this end, UCSC has piloted two new courses: one that focuses on bringing applicable technical and process skills to non-majors and the other, a project-based service learning course, serves as a feeder for senior capstone. Both courses attempt to facilitate legitimate peripheral participation across sectors that enhances a sympathetic accumulation of knowledge and common vocabulary between multidisciplinary team members. As instructors and mentors of capstone projects, we must adequately prepare learners to overcome challenges associated with truly multidisciplinary teaming. In order to effectively accomplish this objective, we propose that the diversity within the teaching team must accurately reflect and represent the necessary diversity of the capstone project teams; that is, incorporate instructors from other departments and divisions across campus.

Client-Oriented to Human-Centered Design

In summary, professional self-efficacy can be the emergent outcome of an academic environment that provides for scaffolded "authentic" engineering. Here, we characterize the term *authentic* as design thinking, project buy-in and ownership, instructors and learners interacting as equals, and a system that allows for and supports differing levels of real-world impact, depending on learner comfort and motivation. The mantra "professional engineers do not design in a vacuum" can be heard from the teaching team throughout the year; the meaning here is clear: project success is directly related to the team's ability to relate to the client and translate constraints into an optimized design.

Learners entering their senior year are generally ill-prepared for empathic design, a skill required of all projects that have implications beyond technical. In canned projects and even in self-conceived projects, constraints tend to be dictated as a constant, e.g. "the robot must navigate the course in under 10 seconds" or as a limitation in cost. It was not until SDP mandated the inclusion of an identified client or customer base that students began to ask the questions: who are we designing for? What are the constraints and priority for the customer? Still, the responses would be limited to a fairly linear and almost egocentric logic.

SDP addresses this issue by incorporating explicit human-centered design programming into the curriculum through the mock project and supporting design notebook. This framework provides experience, equipping learners to understand project criteria and potential impacts through four lenses of sustainable design: technical, social, economic, and environmental. Students not only build empathy for the client in real-world context, but this experience also serves to break down biases towards teammates, demonstrating the need for collaboration with outside expertise that formulates impactful solutions. Emergent innovation directly reflects team cohesion, a state in which teams perceive diversity as requisite to project success and employ effective communication signifying legitimate interdisciplinary engagement [11,25].

Part 3: Challenges and Lessons Learned

There are many challenges associated with the effective implementation of a multidisciplinary engineering capstone course, both pedagogical and logistical in nature. Part of the instructor's responsibility is to identify suitable projects for the capstone, but "suitable" is a highly subjective term that is qualified by leaners' capabilities, as well as the clients' ability to define clear goals and objectives. Forming teams around these projects can be equally or even more nebulous. Successful projects necessitate learner buy-in and multidisciplinary expertise, the latter of which can lead to disparate and dysfunctional team composition (as touched upon earlier in this paper). Fair and accurate assessment of individual learner outcomes in these cases becomes difficult and subjective, as a traditional rubric cannot be consistently applied to all teams. These obstacles become amplified as the program grows and undergoes difficulties associated with scaling.

In this section, we will discuss our approach in addressing these obstacles, some of which have not yet been fully surmounted. **A principal lesson learned is the necessary reliance on faculty able to materially contribute to the student-centered learning paradigm**. Instructors providing the first tier of mentorship that continues throughout the academic year are important to mitigating aforementioned issues. Instructors and TAs must have teaching assignments that ensure teams will work with the same faculty and teams spanning the entire sequence. Faculty cannot be assigned ad hoc but must have both the experience and pedagogical skills to competently teach and mentor capstone learners. Engineering is a learned profession. Imparting the norms and values – the essence of professional practice – requires a period of internship. Beginning this process in students' senior year greatly enhances their chances for successful and enduring employment.

Instructor Reflection

Project Identification:

Projects suitable for student learners must be appropriate in scope and level of challenge. Over the years, instructors have informally defined the "Rules of Senior Design Projects:"

1. Projects must be open-ended and address learner prior knowledge, ideally correlated to their chosen elective coursework.

2. Clients cannot manage projects, the teams are responsible for project management
3. Clients cannot design for the team
4. Clients must allow latitude to fail

Initially, instructors work alongside clients to help identify, filter and shape projects before they are pitched to students in the classroom. They apply a Goldilocks approach: projects that do not require sufficient engineering design or already have a solution identified for the team are deemed too easy, while projects that would normally require a professional external consultant are considered out of scope.

Generally, projects are sourced from corporate-sponsors, clients from Engineering through Student Service, campus staff and faculty, as well as the local municipality; the latter usually relating to collaborative sustainability. Once projects are vetted by instructors, clients complete the project brief, a template form meant to ensure all relevant introductory information is addressed and available to students. This serves as a framework for the project pitch, designed to acquaint students with the project *before* the pitch is made. As a result, students tend to have more poignant and targeted questions for the client and make better use of limited class time.

In spite of best efforts at the outset, there are always difficulties with clients during the year. Teams generally face two extremes: the unresponsive client and/or specification creep. By introducing formalized project proposals, deliverables are negotiated and agreed upon before any project is taken on by the team; the document serves as evidence of mutual consent of the outcomes and contributes to a sense of independence by the team. Otherwise, teams practice customer management explaining or justifying their design decisions to the client – which may result in instructor intervention, as needed. The deliverables articulated within the design notebook can play a very useful role in limiting specification creep.

Team Selection:

Noted earlier in this paper, a critically important component is that students self-aggregate to form teams in a process completely run by the students, removing the instructor filter at the onset. However, candidate teams must ultimately be approved by instructors and stakeholders in order for teams to satisfy the requirements of the fall quarter and move on to the implementation phase in winter. As part of this approval process, teams must justify each individual's membership by having them demonstrate applicable skills or the capacity to develop knowledge and skill requisite for their project's projected success. Not only must students have the background they must also individually justify their inclusion and specific perceived role on the nascent team. This means they must develop a well thought out division of labor that makes sense to the team and the teaching team.

Self-selection is an important social aspect that emphasizes at the outset personal responsibility, realistic assessment of technical skills and how these skills fit into the wider context of engineering design when performed *as a team.* It encourages and enables a guided transition from being a student to being an independent professional.

Students habituated to their role as *students* struggle with the team formation process which typically carries on into the design phase. This and other maturity and attitudinal barriers may set up teams for project failure, i.e., the project did not achieve goals specified in the proposal. Yet, this does not mean the team fails the course if the attitudinal barriers are teachable; learners able to understand how to better define or redefine their project by the end of the program are considered successful.

Individual Assessment:

Student assessment is predominantly the responsibility of the instructor, though is also based in input from project clients, external mentors, and the students themselves. The final student grade is derived in part from individual performance (40%) and also from overall team performance (60%). Similar to other capstone courses [1,26], this program weighs documentation, presentation, and actual participation in the design process more heavily than the final product. When reviewing learners for assessment, a generalized rubric attempts to answer the following questions:

- Did significant learning happen? (evidence of internalizing engineering practice)
- Did it draw upon prior knowledge? (evidence of technical skill)
- Did the student apply new knowledge? (evidence of efficacy)

As alluded to above, project failure can be acceptable if defined by a reason for failure that leads to significant lessons learned. How failure is justified is critical to grade assessments. We show students the famous IDEO video during the first quarter and discuss what Dave Kelly means by "fail often to succeed sooner" [27]. Successful engineering design is an obtuse, intuitive and often muddy, open-ended activity not easily reducible to the simple didactic bottom-up, linear, and wholly predictive learning models characteristic of their earlier coursework. Solving single problems is relatively easy, but how to solve the bigger problem of how a group of many smaller problems should be related is much more difficult, since some of these will be societal and not reducible to simple algorithmic relationships. We have found this paradigm shift is difficult to teach, since it depends on systems thinking encompassing cultural, societal *and* technical aspects. Learning to think in wholes is an attainable and worthy goal, rather than as atomized parts simplistically and conveniently fitting together by assembling components solely according to equations. Entrepreneurially-minded project thinking is chiefly distinguished by this paradigm shift and ultimately produces more desirable graduates.

Conflict Resolution:

The teaching team ensures that teams recognize the existence and likelihood for real conflict within the team. Rather than entering the collaborative environment in denial, teams determine a strategy to address potential conflict in their charter. They reflect on case studies discussed during lecture, share their own experiences, and identify what may be particularly irksome or disrespectful to them. By visualizing potential scenarios, learners bring sharp focus to their own behaviors during meetings and interactions so that team members can check themselves while also having a mechanism to check others.

Periodic self and peer evaluations allow for early identification of differential technical performance and attendant skills along with sometimes difficult team dynamics, such as chronic tardiness to meetings or external academic prioritization. Interventions are usually carried out by team members during the post evaluation meetings, though instructors mediate if they are requested by team members or if they consider it necessary. "Conflict Resolution" as specified in the team charter together with self and peer evaluations certainly do not act as a preventative measure for all situations – conflict still exists, but it does provide a mediating and graded framework from which to act *before* teams reach a breaking point. The charter and peer reviews provide an avenue for due diligence in warning students of poor quality participation in the team that may lead to failing the course (getting fired).

Students once committed to an approved project are normally required to stay with that particular project until completion. Extraordinary circumstances must prevail before a member can leave or be added after the team charter is finalized. Ideally, early indicators of conflict are invariably evident in self and peer evaluations and hence will properly surface at a group level in the candid discussion of team dynamics following the self and peer evaluations. This is true for the majority of teams and adequately addresses most conflict experienced within the course. To date, instances of irrecoverable conflict are rare though do occur, and are usually due to one of two reasons: 1) lack of technical competence resulting in the inability to perform work promised to the team, and 2) lack of commitment. The latter is usually resolvable, while the former often is not. In either case, members must pull their own weight and are not permitted exist in the shadow of better performing students. In the first case, teams either internally reorganize to effect a better division of labor, and/or invoke the procedure outlined in their respective charters to terminate a member. We expect teams to learn to manage themselves and address such issues collectively before appealing to the teaching team in those cases where no resolution is considered possible. At this point an executive meeting is held to openly discuss resolution in a professional and objective manner.

An example of the first case involves a large team of seven students segregated internally into smaller sub-teams dedicated to software development, circuit design, system integration etc. Unable to complete their mutually assigned and agreed upon workload, one student's tasks were consistently picked up by other student engineers. After several repeated warnings, carefully delineated by their team's charter, the entire team recommended termination. A mediating executive meeting was held with the teaching team (instructor and TA) and the decision upheld. At this point a student fired from a team for cause has only two options: fail the class or elect to satisfy the graduation requirement as a sponsored senior thesis – though it is the student's responsibility to identify a thesis-worthy project and advisor. In this particular case, another team of two robotic engineering students had painfully discovered their project necessitated a third member and they solicited the student to consider joining them. This action was *approved* by the teaching team but not required.

Scalability:

The scalability of the Senior Design Program has been tested by the burgeoning student enrollment. Next year, the school of engineering will pilot a second cycle of the 15 unit sequence beginning in spring quarter, that way teams may utilize what would become dedicated senior design resources in the summer/fall. Moreover, project proposals will now have a rolling deadline; projects that were unable to commit before fall quarter team selection (especially corporate-sponsored ones) will have an additional opportunity to engage a team. Furthermore, out of sequence students or those who failed to join a team for whatever reason will have also have this additional opportunity. Beyond this fix, the availability of space and to a lesser degree appropriate instructors, will constrain program growth if the enrollment numbers continue to climb.

Discussions to address scalability have yielded limited options for consideration: re-implementing "canned" or preselected projects, reverting back to a two-quarter sequence, or limiting enrollment to the best performing students. However, these options all have *demonstrated* detrimental pedagogical implications. Learners require more time in preparation for professional engineering practice, especially when not only conceptually designing a solution but actually fabricating a prototype or product; coursework must provide an avenue for understanding and achieving this outcome. On the final point, students that perform exceptionally in SDP are not necessarily the ones entering the program with the highest GPAs, and vice versa. Scaling the course to accommodate the BSOE growth will require a formalized model to maintain quality, one that engages the entire school of engineering. We are in the process of involving all BSOE faculty in determining what this will look like.

Learner-Identified Challenges:

Many changes to the capstone program are a direct result of feedback from instructors, industry sponsors, ABET, and other external evaluators. However, it is predominantly the responses from the students themselves that has fundamentally shaped the course into its present form, and will continue to do so moving forward. Several themes consistently emerge in the exit interviews:

First, and most prominent, the need for earlier exposure to real engineering design experiences to augment the technical formalism of simple predictive, math-based problem solving. One student stated it as "*More hands-on experience and context from the beginning, to create a thread of understanding of topics throughout the EE curriculum.*" This has implications beyond the capstone sequence, deftly touching as it does, on how we traditionally teach contemporary engineering. Entrepreneurially-minded learning requires a revolution in how we viably build a solid foundation in theory and practice. We have sought to address this with several upper level design classes; students readily acknowledge their value but also note they need to come earlier in the curriculum to be of any real value for the capstone class.

Second, mundane basic practical lab skills, such as soldering, lab safety and circuit design, need to be emphasized and continually practiced earlier in the curriculum. In 2006 we created a class, "Introduction to EDA Tools for PCB Design" in response to the need for capstone teams to implement circuit designs, though this action is not a catch-all solution. Again, the curriculum as a whole needs to be fluid and adaptable to the changing needs of the professional environment.

Third, learners feel anxiety towards obtaining and performing well in employment upon graduation. "*I found that I had no idea what electrical engineers are actually doing in industry…I did gather this information in the [capstone] series*." To address this item, we introduced corporate-sponsored projects affording students significant contact with industry and possible job opportunities. Furthermore, communication, connection and interaction with diverse stakeholders are fundamental to "understanding impact of solutions in a global/societal context [14]." Working with both industry and student service entities promotes collaborative experience across disciplines and sectors, allowing learners to gain real, professional experience that helps to build confidence and transition learners beyond graduation.

> "*I believe the most useful part of my undergraduate training took place during the capstone series. Many of the information and skills I got out of both attending lectures in the [fall] and interacting with fellow engineers and supervisors on a project in the [winter/spring] will directly apply to professional life in engineering…it was very helpful for me to gain experience working with fellow engineers and managers so I can understand what it will be like in the corporate world*."

The UCSC Senior Design Capstone Program is a culminating opportunity to *apply* learned engineering knowledge and skill in a real world, yet scaffolded environment where students may better understand and employ authentic engineering practice. However, instructors and the students themselves have recognized that learners are not adequately prepared before the capstone course, shifting emphasis away from *application* toward *accumulating and understanding* new content. The capstone program effectively addresses learner preparation in the initial weeks, where the course is heavily structured with both class and project in parallel before moving to a project-focused framework where 'formal instruction' is less prominent, though much of this content could and perhaps should be introduced earlier in the undergraduate engineering program.

Fundamentally, the distinction between *preparing* students for a culminating engineering design experience as a project course is artificial. The "*thread of understanding*" mentioned above refers to an indivisible conceptual relationship between theory and practice. The typical sequential paradigm presumes that preparatory coursework somehow causes ipso facto the conceptual ability to do engineering design displaced later in time. It doesn't. If possible, there should be more focus on entrepreneurially-minded and professional efficacy within the engineering curriculum as a whole, which could release resources at the end of the learner's undergraduate career to focus on more subtle and individualized relationship between theory and professional practice made possible through informal and contextual mentor dialogue and interaction.

Conclusion:

This reflection has touched upon the history of the capstone course at BSOE, identified significant changes that have incrementally contributed to the pedagogical development of the course sequence from single-learner to project-based learning to that of entrepreneurially-minded learning. Our original, prescriptive single-learner, single-quarter class transformed to embrace multidisciplinary or collaborative PBL in our two-quarter capstone that began to center around client-oriented design. After the addition of corporate-sponsors in 2012, the capstone became a three-quarter sequence with a 2-unit fall, 5-unit winter and 5-unit spring unit load, which facilitated entrepreneurially-minded outcomes in tone and format. The inclusion of three basic documents within the design notebook that codify the project overall has been instrumental in the progress of the course – the project framework, project proposal and team charter. It wasn't until 2017 that we streamlined the curriculum to inclusively treat ethics and disciplinary communications (technical writing), putting them both in their proper context of team-based engineering design by increasing the fall quarter to 5-units. This has enabled us to explicitly develop the fundamentals of entrepreneurially-minded engineering as a natural progression in the fall quarter with the unique addition of the Mock Project and a deeper discussion of human-centered design.

After 20 years, the major challenge now in continuing this progression is how to synergistically integrate liberal arts and engineering disciplines as truly cohesive *teams*. Besides the logistical challenges of incorporating disparate disciplines, a new paradigm embracing the intellectual diversity that defines a social context and truly enables genuine collaborative teamwork needs creating. We point out to students that IDEO's famous "Deep Dive" shopping cart project had members from a wide range of disciplines. Such diversity needs to happen on both the student side and faculty side of the equation.

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