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Cultivating the Capstone Ecosystem to Educate the Engineer of 2020*

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Capstone design courses often provide authentic learning opportunities and real-world responsibility at the conclusion of students' undergraduate engineering education, helping prepare them for their career and life trajectories after graduation. Cultivating the broader capstone design ecosystem can further enrich students' learning, expand student connections, and facilitate acquisition of the Engineer of 2020 attributes. This paper presents a framework and associated strategies for a capstone design ecosystem that extends across the capstone design course, across the engineering department, across the institution, and across the alumni community. The paper discusses implementation of the proposed ecosystem approach as a case study supplemented by student testimonials and survey results from students and alumni regarding impact. Capstone educators are encouraged to try these strategies, in part or in whole, within their own institutions so as to improve capstone design experiences and better prepare students for engineering in 2020 and beyond.

Keywords: capstone design; ecosystem; Engineer of 2020; shadowing; alumni engagement

1. Introduction

Capstone design courses are a widespread component of engineering education in the US [1, 2]. They provide students a rich learning opportunity to apply their previous coursework, explore new skills and knowledge, and prepare for their transition to life after graduation [3]. Many capstone courses involve students collaborating in teams on applied design projects with external sponsors, thus providing students with authentic learning experiences and real-world responsibility [1, 4–8]. Engineering departments commonly look to their capstone design courses to demonstrate achievement of ABET outcomes.

While capstone projects are often the focus of the capstone design experience, the broader capstone ecosystem includes components and strategies that extend student connections beyond the immediate capstone project team: across the capstone design course, across the engineering curriculum, across the institution, and across the alumni community. Cultivation of this broader capstone ecosystem enriches the overall capstone design experience and promotes many of the attributes of the Engineer of 2020 [9], especially communication, leadership, professionalism, business and management, lifelong learning, practical ingenuity, and agility and resilience. This paper proposes (1) a robust capstone ecosystem framework with specific cultivation strategies, and (2) evidence of successful implementation in an existing capstone design course.

2. Capstone ecosystem framework: strategies and motivation

The capstone ecosystem is both broad and multifaceted, with many layers and opportunities for cultivation far beyond the capstone project itself. Figure 1 provides an illustration of the layers within the capstone ecosystem, radiating outward from the nucleus of the capstone project team. Each layer itself includes a variety of cultivation strategies to enrich capstone education, examples of which are discussed below along with their motivation and learning benefits.

2.1 Across the capstone design course

While the focus of capstone design courses is typically the design projects, many other types of interaction and connection are possible across project teams and in the course overall. Specific effective approaches include cross-project discussions, project management cohorts, and cross-project shadowing.

Cross-project team (CPT) discussions—i.e., small groups of students representing multiple capstone project teams—provide an easy opportunity for students to exchange ideas, challenges, and strategies with classmates on different projects. CPTs can be implemented early in the capstone course to share information about the project sponsors and liaison interactions so everyone in the class gains exposure to different companies and government organizations. Heading into the end of each semester, CPTs can discuss team challenges, provide advice, and share strategies for success. Before the end of the projects, CPTs can

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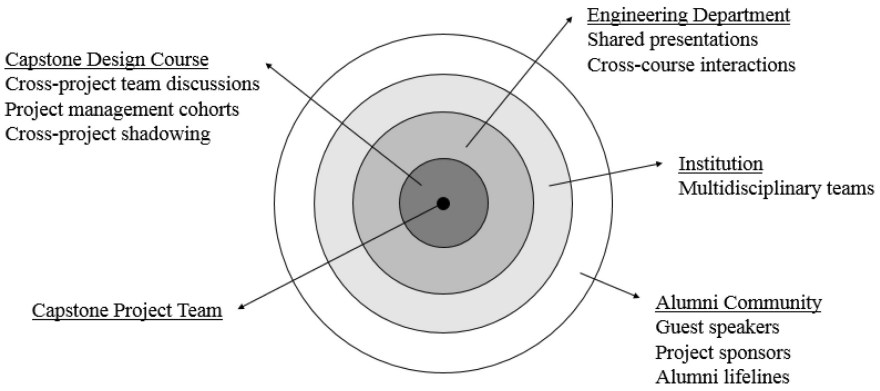

Fig. 1. Capstone Ecosystem Layers and Cultivation Strategies.

review team posters, offering suggestions for edits before the final versions are printed. CPTs can also serve as the unit for small group work in class sessions, such as engineering ethics case discussions. In all of these experiences, students talk with and learn from each other, extending their own capstone design experiences.

Another way to connect students across projects is through project management cohorts, i.e. the collection of students serving as the project manager (PM) for their capstone design team. Convening the cohort of PMs in discussion allows PMs to share challenges and questions with the course instructor and links the PMs to others going through the same experience from whom they can seek advice. This approach works especially well for capstone courses that employ a rotating project management role, with each team member serving as PM for that team for some portion of the course. Although all PMs have at least some similar responsibilities, in the rotational system each PM cohort has challenges and responsibilities specific to its time of rotation (i.e. project scoping, conceptual design, or project conclusion/delivery).

A third option to create linkages among students and teams is through project "shadows", a strategy in which each student is assigned to shadow one other design team over the course of the year. (Shadow assignment could be based on request or by student expertise or at random, depending on instructor preference. One suggested approach is to ensure that students who do not get their first choice for the main project are automatically assigned to that choice for shadowing.) While the extent of shadow involvement may vary, one especially useful approach is to leverage shadow cohorts as reviewers for the formal design reviews of the capstone teams. To prepare for these reviews, shadows can meet briefly with their assigned team several times during the year (using a format such as a "10-minute stand-up meeting"), can have access to the team's project materials on their course management page or website, and can occasionally attend a coach or liaison meeting with their assigned team. The educational benefits of shadowing are that students gain exposure to a project other than their own, providing context for their own capstone experience and opportunity to contribute to more than one project.

2.2 Across the engineering department

Learning in and from capstone design can also extend beyond the course itself, and into the rest of the curriculum. Shared presentations and cross-course interactions are two easy strategies to build those connections. Many capstone design programs culminate in a final presentation or "design expo" that showcases the capstone team projects [3]. This is an excellent opportunity for capstone students to communicate their process and outcomes for a diverse audience. Linking this event with the final presentations of other design classes enriches the experience for everyone. For example, introductory engineering design students could showcase their project posters or prototypes before or during a break in the capstone design end-of-semester presentations, thus connecting the two bookend design courses. At such a joint event, capstone students could ask interactive questions of the intro design students, and/or the intro design students could provide near-real-time feedback for the capstone students using a short review form. The juxtaposition of the two presentations illustrates to the capstone students how much they have learned in the intervening years.

2.3 Across the institution

Engineering rarely happens in a vacuum; rather, it is situated in a broader, multidisciplinary context. As such, the Engineer of 2020 [9] must be an effective collaborator who recognizes the ways in which social, economic, environmental, political, and

technological factors are intertwined. Capstone design courses have traditionally been focused within a single discipline, but multidisciplinary capstone design courses are becoming more common, including some that integrate engineering with business, health sciences, arts, and/or humanities [1, 11–15]. The impact of these collaborations extends beyond just the students on the project teams since all the students in the capstone design class (especially those shadowing these projects) learn about the partnerships and see the process of engineering in context.

2.4 Across the alumni community

Engaging alumni in the capstone design course is an especially powerful strategy for fostering leadership, professionalism, lifelong learning, networking, and resilience. Several effective strategies include hosting alumni as guest speakers and sourcing projects from organizations with alumni liaisons. Alumni speakers provide a rewarding way to build connections with alumni and enrich the current student experience. As noted by Halversen et al., from their alumni survey at Brigham Young University [16], just hearing capstone stories and advice from alumni can help boost the confidence of current capstone design students; alumni, in turn, remain connected to their alma mater and help mentor the next generation of graduates. Engaging alumni as capstone project sponsors is a strategy employed by many capstone design courses nationwide; according to the 2015 capstone design survey, 49 respondents specifically noted that alumni were a significant source of projects [1].

An additional approach for connecting alumni with current students is via an ''alumni lifeline'' initiative, in which each capstone team is matched with an alumnus within one or two years of graduation. This targeted matching intentionally closes the loop on capstone design, connecting those who have only recently completed their own capstone design experience with those just beginning. Implementing the alumni lifeline strategy requires a little work from the instructor at the start of the class (inviting the alumni lifelines, establishing the matches, and encouraging the initial team-lifeline connection) but can be self-sustaining thereafter; the topics and frequency of conversation can be left to the discretion of the students and the lifelines.

3. Implementing the capstone ecosystem: case study at Smith College

The aforementioned cultivation strategies have been implemented successfully in the capstone design course at Smith College, demonstrating their logistical viability. To capture first-person perspective and direct impact, Smith capstone students and alumni were surveyed in 2016–2017 about their experiences and opinions with different ecosystem elements. Table 1 details the survey format, topics, and response rates for the four different surveys. The results of the survey, both qualitative and quantitative, are discussed below, following an overview of the Smith capstone design course.

3.1 Design Clinic overview

Smith College's engineering capstone course, ''Design Clinic'', was launched in fall 2003 with the inaugural senior class of engineering students. Like many capstone design courses in the US [1], Design Clinic is a two-semester capstone design course in which students collaborate in teams on real-world projects sponsored by industry and government. Team size is typically three to four students but has been as large as six and as small as two. The number of teams varies depending on class size but has ranged from six to nine in recent years. Teams each work on their own externally-sponsored projects, meeting weekly with their sponsor liaison(s) and weekly with the Design Clinic Director, who coaches all the teams. Smith's engineering program is a general engineering degree, so the capstone projects span a range of engineering disciplines.

3.2 Impact of shadowing

Design Clinic launched the shadowing program in

Table 1. Experience and Opinion Surveys for Design Clinic Capstone Students and Alumni

Recipient Group	Survey Format and Topics	Response Rate
Capstone Students (AY 2016–2017)	Mix of categorical and open-ended questions on shadowing, alumni speakers, alumni liaisons, and alumni lifelines	68% (17 of 25)
Alumni Guest Speakers and Panelists (2013–2017)	Open-ended questions about justification for and value of participation as a guest speaker or panelist	32% (12 of 37)
Alumni Liaisons (2013–2017)	Open-ended questions about justification for and value of project sponsorship and liaison participation	83% (5 of 6)
Alumni Lifelines (AY 2016–2017)	Open-ended questions about justification for and format and value of participation as an alum lifeline	57% (4 of 7)

2014 and has continued it since. Overall, Smith student response to shadowing, both being shadowed and serving as a shadow, has been largely positive, as shown in Table 2. When asked what they liked most about shadowing/being shadowed, many students commented about gaining a window into other teams and receiving new ideas, with sample comments such as the following:

> "Shadowing provides me with an opportunity to learn different projects and get to know my project from different perspectives."

and

> "The experience of being able to critique a project is one that is valuable, and I would not have the same learning experience or benefit if I were doing so with my own project."

Responses to the question of what students liked least about shadowing/being shadowed mostly centered around lack of time:

> "I don't enjoy the time commitment, but at the same time, I wish I had more time to invest in being a shadow so that I could really get to know the project and play a larger role in whatever part they ask of me."

Regarding changes to make the shadow experience more effective for learning, several students suggested that the 10-minute stand-up meetings be more structured and/or more often, so shadows could stay up to date with their projects.

3.3 Impact of multidisciplinary teams

For several years, the Design Clinic class has intentionally included projects with cross-disciplinary collaborations. In 2015–2016, one of the Design Clinic projects involved students and faculty from engineering, computer science, and anthropology, in collaboration with doctors and nurses at a local pediatric clinic, on the design of a digital version of a pediatric screening form. In 2016–2017, students and faculty from engineering and landscape studies collaborated with the local Northampton, Massachusetts planning office on the design and siting of mobile parklets for the local downtown business district. In 2017–2018, one Design Clinic project involved students and faculty from engineering and education on the design of more inclusive dolls for long-term hospitalized children.

In both these collaborations, students leveraged the skills and approaches from their own training and learned to collaborate with team members from different disciplines. They also experienced engineering in context, including stakeholders with a variety of expertise and perspectives. As one student noted:

> "Interestingly, we realized, halfway through the [fall] semester, the importance of focusing on what we are good at. Initially, we all kept trying to do everything. However, we realized that each of us has our own skill and that, if we capitalize on these skills, we are much more productive. Realizing this really helped us take our project and our team relations to the next level."

Another student expressed a similar thought:

> "This experience has taught me how to combine my knowledge across fields and how to have fun while working with others."

Regarding liaison interaction, one student noted:

> "[A] challenge we had at the beginning was interpreting ideas from our liaisons. We often got a lot of ideas from our liaisons and sometimes they were conflicting. . . . This added different layers of technical as well as logistical complexities to our project."

The experience of working in a multidisciplinary and multi-stakeholder setting will no doubt provide these new graduates with skills and knowledge about working on teams that would be expected of more seasoned professionals.

3.4 Impact of alumni engagement

In the past five years, more than 55 Smith engineering alumni (about twice the size of the Design Clinic cohort each year) have been involved with Design Clinic as guest speakers, project sponsors, or alumni lifelines.

Since its second year, Smith's Design Clinic course has featured alumni as guest speakers through in-person panels ("Life After Smith" and "Work/Life Balance") and virtual "Career Spotlights" via video conference. Student responses were uniformly positive about alumni engagement as guest speakers and panelists, as shown in Table 3.

Table 2. Smith Student Responses to Shadowing

Survey Question	Likert Response* (#)				% Agree or Strongly Agree
	SD	D	A	SA	
Receiving feedback from shadows during design reviews is helpful to my team.	0	3	10	4	82%
Shadowing a different team is helpful to my own learning	0	1	13	3	94%

* Scale: SD = Strongly Disagree, D = Disagree, A = Agree, SA = Strongly Agree.

Table 3. Student Responses to Alumni Engagement as Speakers and Panelists

Survey Question	Likert Response* (#)				% Agree or Strongly Agree
	SD	D	A	SA	
Interacting with alumni speakers/panelists is valuable to my own professional development.	0	0	5	12	100%
Career Spotlights are an effective use of class time.	0	0	6	11	100%

* Scale: SD = Strongly Disagree, D = Disagree, A = Agree, SA = Strongly Agree.

Student responses regarding what they liked most about interacting with alumni centered on two primary themes: learning about different career paths and mitigating student fears, with responses such as

> "I liked hearing that it is ok if I don't have it all figured out and that there are MANY directions I can go with my degree."

Alumni were equally positive about their experiences as speakers and panelists, both in their reasons for participating and the value they gained. Sample responses included the following:

> ". . . I love giving back and I think it is important to share the message that there is not one path and the path is often not straight.'
>
> "I was excited to be invited to speak as it was my turn to share my industry experience and tie it with my Smith education."
>
> "I was able to learn about life after Smith from the other panelists as well since they were further along with their career path than I was."
>
> "It was energizing to see the motivated students."
>
> "It made me take a step back and look at the big picture of my career and what I do on a day-to-day basis."

More recently, Design Clinic has looked to alumni for potential projects and, in particular, for alumni liaisons. The capstone students truly value collaborating with a liaison who has been in their very shoes and who now serves as a role model and supporter for them. As one student noted:

> "[Our liaison] knows the expectations of the project and the structure and some of the lingo. It makes it easier to communicate with her because she knows exactly what we are dealing with."

Alumni liaisons offered multiple reasons for supporting a project collaboration with their companies, with comments such as the following:

> "I wanted to contribute to the program that developed me into the engineer I am today."
>
> "It was an opportunity . . . for my alma mater to help us with a project that we hope will shape the future of the products we make."
>
> "I have such a strong passion for the work that I do at my company that I wanted to share it with students and get them learning and excited about the type of work that I do."
>
> "I also love helping out students and want to do all I can to support that!"

All of the alumni liaisons who responded to the survey found the liaison experience to be valuable for them, highlighting the enjoyment of both teaching and learning from the students, sharing experiences and advice, and gaining a useful product for their company. One respondent specifically commented on the professional development she gained from the liaison experience:

> "At my company there is not a lot of room for upward mobility, so this experience let me take a leadership role and expand my management skills where there isn't normally an opportunity to do so."

Design Clinic piloted alumni lifelines in 2016–2017, matching each project team to an alumna within two years of graduation. Based on the survey data, the lifelines valued the experience for the continued connection to their alma mater and the opportunity to serve as a mentor and resource:

> "I felt lucky because I got to relate back to my days at Smith through this connection and hopefully put some things into perspective for my team."

Interestingly, although only about half the teams had actually connected with their lifelines, both students and alumni appreciated the potential for contact. For example, a student commented:

> "It's nice knowing we can reach out to someone who's been through the process before"

and an alumna commented:

> "I have certainly enjoyed knowing that my team can contact me at any time should anything arise."

4. Conclusions and transferability

Capstone design courses already provide a multifaceted learning opportunity at the conclusion of students' undergraduate engineering education, helping prepare them for their career and life trajectories after graduation. This paper details a number of strategies for cultivating the broader capstone ecosystem across the capstone design

course, across the engineering department, across the institution, and across the alumni community. The goal of such cultivation is to further enrich students' learning experience, expand student connections, and facilitate acquisition of the Engineer of 2020 attributes. The paper discusses the implementation of the strategies in the capstone design course at Smith College; student testimonials and survey results demonstrate the positive impact of such an ecosystem approach.

Capstone design educators are encouraged to implement these strategies within their own institution and capstone design program. The strategies are structured such that they can be adopted incrementally over time; even small steps would help cultivate the capstone ecosystem. For example, an instructor could start by assigning students to review another team's presentation before implementing the full shadow initiative. Likewise, cross-project team discussions could be piloted in part of a single class or conducted multiple times. Simply inviting other engineering classes (and class years) to the capstone design presentations offers benefits to both presenters and audience; enabling shared presentations only increases the positive impact. Collaborating with faculty outside engineering and alumni outside the institution is easiest to start with those who already are interested in such partnerships; paving the way through success with kindred spirits helps convince others for future such opportunities. Most importantly, thinking beyond the core of the project team and extending one's reach across the wider ecosystem serves to improve capstone design experiences and better prepare students for engineering in 2020 and beyond.

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