Course-Based Undergraduate Research In Upper-Level Engineering Electives: A Case Study

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Abstract

Course-based undergraduate research experiences (CUREs) have been implemented and studied throughout the sciences, with well-documented benefits now clear for both students and faculty. Despite their increasingly widespread application, there remain very few documented implementations within engineering curricula. In the present work, we describe the design, implementation, and evaluation of a CURE module in an upper-level engineering elective, specifically a junior-level fluid dynamics course in mechanical engineering. By coordinating the increased availability of rapid-prototyping equipment with real research needs across campus, student participants were successfully engaged in a semester-long research experience with prolonged impact. In each project, student groups were tasked with designing, fabricating, documenting, and sharing a rapidly-prototyped device that could be used to measure or generate fluid flows. Details of the course motivation, design, learning outcomes, and deliverables are described herein. Quantitative assessment of the course was also conducted, which highlighted improvements in the students' self-perceived efficacy as scientists and engineers after completing the course module. As has been demonstrated in other scientific fields, CURE courses are a potentially powerful mechanism to increase accessibility and diversity in engineering research.

Introduction

Since the concept of incorporating research in the classroom was formalized by the Course-Based Undergraduate Research Experiences Network (CUREnet) in 2014 (Auchincloss *et al.*, 2014), many examples of CUREs have been implemented and documented in disciplines including biology, chemistry, astronomy, geology, and nursing (Dolan, 2016). A majority of published cases are from the life sciences (Dolan, 2016), and while the benefits for these disciplines are well documented, they are not the only group that could benefit from increased exposure to academic research. More traditional undergraduate research experiences (UREs), where students are mentored by a faculty member on an independent research project, have been associated with increased likelihood to obtain graduate degrees, enhancement of cognitive skills, improvements in communication, and increased self-identification as engineers (Linn *et al.*, 2015; Russell *et al.*, 2007). However, mentored UREs are not equitably accessed by students; leading to self-selection of higher performing students in UREs, and intrinsic participation barriers for students from underrepresented groups (Bangera *et al.*, 2014).

The benefits of undergraduate research experiences can be extended to all students by incorporating more research experiences into the curriculum, rather than reserving research experiences for a select few. While there are abundant models of successful CURE implementation in the life sciences and chemistry (Dolan, 2016), there are very few documented examples of the CURE framework being implemented in engineering (Abler *et al.*, 2011; Full *et al.*, 2015). Herein, we present a case study of the development, implementation, and evaluation of a CURE course in an upper-level engineering elective.

A principal motivation that inspired the design of the course is embodied by the concept of "students as producers". This idea, exemplified by the work of Derek Bruff (Bruff, 2019) in the field of mathematics, presents the hypothesis that by expanding the audience of the products of student work in the classroom to field experts, other students, and the scientific community, students are likely to engage more fully in assignments and put forth more effort to produce quality work. This concept of "students as producers" aligns synergistically with one of the five essential elements of a CURE: *broad relevance*, which specifies that student research in CUREs should have relevance outside of their classroom (Auchincloss *et al.*, 2014).

Further, with the increase in makerspaces available to undergraduate students (including the Brown Design Workshop (BDW) at Brown University) undergraduates in engineering increasingly possess new skill sets that are directly translatable to advances in experimental engineering research. These expanding resources available on many campuses in the form of 3D-printers, laser cutters, and other rapid-production equipment, can help facilitate undergraduate involvement in high-level, novel research (Ionkin & Harris, 2018), but are currently underutilized. The proliferation of rapid-prototyping techniques in academic research is well captured by the emergence of peer-reviewed publications that focus on "open hardware", including HardwareX, the Journal of Open Hardware, and others. The steady movement towards open hardware has an immense capacity to increase both repeatability and accessibility of science.

Project-based learning is far from a new concept in the engineering curriculum, and is in fact now fundamental in nearly all engineering education programs. Most commonly, project topics in the engineering curriculum (e.g. within a cornerstone or capstone design course) are either fabricated by the instructor or sourced from industry (Dym *et al.*, 2015). A distinguishing feature of the present course is that the projects are dictated by needs in the research community, specifically. Furthermore, the engineering CURE described here would ideally be offered in the intermediate years of the undergraduate curriculum; late enough that technical engineering skills have been developed and can be applied, but early enough to allow for meaningful impact on students' professional trajectories. Introducing courses such as these earlier into the undergraduate curriculum also has the potential to increase diversity in STEM by lowering the barrier to independent undergraduate research for historically underrepresented groups including women and minorities as a first step towards a career in academia. The relationship between our course and more traditional project-based courses in Engineering is reviewed in more detail in the Discussion section.

Beyond being of benefit to students, faculty and their research programs also have potential to benefit from engaging students in relevant research experiences in the curriculum. While faculty outcomes such as publications, connecting research to teaching and service, and increased excitement and engagement, have been documented in other fields (Shortlidge *et al.*, 2016; Shortlidge *et al.*, 2017), engineering programs stand to uniquely benefit faculty by better satisfying program accreditation requirements defined by ABET (ABET, 2019). Each of the seven Student Outcomes that must be documented by an engineering program to receive accreditation can potentially be supported by the implementation of such course-based research projects. These requirements focus predominantly on technical engineering skills, communication, collaboration, and active experimentation, and thus have considerable overlap with many of the anticipated learning outcomes of a CURE course. The ability for students to be experienced in addressing real-world and open-ended problems has been increasingly emphasized in these requirements, in direct response to the needs of both industry and academia for practicing engineers (Coleman *et al*., 2018; Dym *et al*., 2015).

In this case study, we will describe the overall design and the intended learning outcomes associated with the CURE course module as implemented in an engineering curriculum. We will then describe the final deliverables associated with the course in each of the two semesters it has been offered, and provide a brief summary of the assignments that built up to these final deliverables. An assessment of student outcomes, summary of sustained impacts, and additional discussion will follow.

Course Description

Course Design and Objectives

The CURE concept was implemented in a design module (referred to as the "R&D Studio") meant to replace the typical lab portion of an advanced fluid dynamics course for undergraduates. This module, required for students taking the course for credit, was run alongside the lecture portion of the course. Previous iterations of this course traditionally had one lab, consisting of the investigation of lift and drag on an airfoil in a wind tunnel, which was heavily pre-prepared and led the students toward re-discovering previously known, studied, and documented results. Such labs do not give students realistic exposure to experimental science; brainstorming, design, and trouble-shooting is typically left entirely to the instructors while only data collection is left to students. Conversely, in most experimental science, final data collection is only a minor portion of the research experience, and tackling unanticipated technical challenges often leads to a deeper, more robust understanding of the results, including their applicability and the uncertainty associated with them. After having taken the course, one student reflected on the broader engineering curriculum mentioning that "...normal engineering courses ask students to learn how to use lab equipment and how to perform experiments with said equipment, then we only use the machines once a semester before writing a formal lab report and never touching the equipment again. That whole model of lab learning feels archaic to me."

With the support from an Howard Hughes Medical Institute (HHMI) grant and the Sheridan Center for Teaching and Learning at Brown, this semester-long module, aligned with the research efforts and interests of the instructors and other faculty at Brown, provided students with the opportunity to pursue projects in alignment with experimental research programs in an engineering lab setting. Students brainstormed, designed, developed, fabricated, and tested experimental devices in fluid mechanics, and shared their results with a diversity of audiences through a variety of different media. Each year, students were informed at the beginning of the semester of the various outlets in which they would be sharing their results. In our implementation, such outlets included blog posts, instructional posts, social media, and research symposia.

The course module design incorporated all five characteristics of a CURE (Auchincloss et al., 2014):

- **Use of disciplinary practices:** Students were familiarized with common experimental protocols, fabrication methods, and measurement devices in fluid mechanics.
- **Discovery of an unknown outcome:** The module focused on designing and testing a novel setup using rapid-prototyping methods, or in some cases, a re-design of an existing experiment using such methods. In both cases, the performance and results were uncertain and were identified through the course of the project.
- **Broadly relevant research:** Project topics were selected based on identified needs outside of the classroom, and the results of which were made available to the communities of interest.
- **Collaboration:** The projects involved teams of three to five students formed at the beginning of the semester. Student groups collaborated with the instructors, teaching assistants, and other faculty members throughout the process.
- **Iteration:** In developing an experiment, it is improbable that the first design will be successful and can't be improved upon. The students iterated throughout the semester on their design, focusing on both accessibility and technical performance.

Recent literature published on CUREs recommends the use of backward design when executing CUREs: defining the goals for the course prior to the development of the course itself (Cooper *et al., 2017*). This is especially important since this course was intended to meet specific objectives related to scientific discovery in addition to promoting student learning. In addition, Cooper *et al.* (2019) found that of the five CURE dimensions, discovery & relevance, when combined, were key to the positive outcomes of CURE courses through enhancement of students' project ownership.

The intended learning outcomes for this course module were:

- Students will apply rapid-prototyping methods increasingly being used in experimental research.
- Students will gain first-hand experience with realistic experimental lab work and experimental design.
- Students will identify technical tools relevant to the fluid dynamics community that can be reproduced by a diverse user base.
- Students will demonstrate proficiency in technical writing and communication for diverse audiences.

We chose to focus on these specific outcomes in the present design of the course module, however a great number of other valuable outcomes could be substituted or supplemented within the broad scope of the CURE framework. Such topics might include engineering and research ethics, sustainability and environmental impact, error analysis and quantification, and technology transfer and translation, among others.

The CURE module was structured to align with a typical 15-week semester. An online survey was developed and utilized by the instructors at the beginning of the semester to form groups of three to five students that were well balanced in terms of knowledge in the field of fluid dynamics, design and manufacturing abilities, team dynamics, and schedule compatibility. All students entering the course had at least some experience and training in the makerspace (Brown Design Workshop) as part of the early engineering curriculum. The standardized training the students receive earlier in the foundational engineering curriculum includes extensive safety training to ensure safe operation of the equipment available in the makerspace. Additional and "refresher" training was offered at the beginning of the semester for the students, in coordination with the makerspace. Each group selected or was assigned an independent research topic. The course has now been offered in two semesters: Spring 2019 (SP19) and Spring 2020 (SP20). A number of significant changes were implemented following SP19 based on student feedback and reflection on student outcomes. Further changes were also implemented in rapid fashion mid-way through SP20 due to the swift transition to fully remote learning as a result of the COVID-19 pandemic. In each year, over the course of the semester, students were guided through a series of assignments intended to highlight the key steps in the engineering research and design process and to provide a scaffold for the final deliverables of the course. In what follows, we will first describe the details of the course deliverables and then outline the scaffolded assignments developed to build up to the final deliverables. Appropriate scaffolding of assignments was critical to encourage students to make continuous progress throughout the semester, as well as to provide numerous opportunities for feedback from instructors, their peers, and other faculty. Furthermore, the major changes implemented from SP19 to SP20 are highlighted, discussed, and rationalized.

Implementation

Throughout the semester, students worked within a group of three to five student peers to identify and fill a need in the research community for an affordable, reliable, well-characterized, and highly reproducible device to create or measure fluid flows. In alignment with the goal of elucidating the nature of experimental research, which commonly involves a significant amount of failure and iteration, this project incorporated several avenues for

Figure 1: Focus on iteration. A student group in Spring 2019 shares their first prototype to the class in the Brown Design Workshop mid-semester (left) and demonstrates their final prototype to the public at the Undergraduate Research Symposium at the end of the semester (right).

Year One (Spring 2019)		
Week	**Studio Topics**	**Corresponding Assignment**
3	Project Introduction + Identifying Projects	Group Contract (Due Week 4) Project Proposal (Due Week 4)
4	Understanding the Design Process	Preliminary Design Review (Due Week 6)
5	Components of the Preliminary Design Review	
6	Preliminary Design Review Presentation	First Blog Post (Due Week 8)
7	Science Communication	
8		First Prototype (Due Week 10)
9	Group Evaluation + Rapid Prototyping	
10	Progress Updates	Device Validation + Testing Plan (Due Week 11)
11	Developing a Testing Plan + Device Documentation	Class Update (Due Week 12)
12		
13		Final Blog Post (Due Week 14) CURE Symposium Demonstration (Due Week 14) Instructables Post (Due Week 14)
14	Reflections	

Table 1: Spring 2019 semester timeline for R&D Studio sessions and assignments.

reflecting on the experimental process and sharing it with various audiences.

Year One

Design teams published **two blog posts** over the course of the semester. The first post was intended to give groups practice with presenting scientific ideas to a general audience, create a scaffolding for the more extensive final blog post encompassing the outward-facing components of their projects, and to provide insight for those reading the blog into the experimental design process. Requiring groups to synthesize their progress mid-project allows insight into the nonlinear trajectory of experimental design and highlights the impact of iteration and missteps in formulating a finished product. In terms of the scaffolded sequence of assignments leading up to the final deliverable, one student reflected that "the structured assignments of the studio showed me how to break a problem into manageable pieces and this has been very helpful in my other classes and research."

The final blog post was intended to summarize team progress throughout the semester, and to provide a status update for the community. Teams either announced that their devices were ready for deployment, or recommended avenues for further iteration and development for other researchers or student groups.

The final blog posts were published on the course website in conjunction with **instructional posts** on instructables.com, a platform for self-publication of directions for creative "DIY" projects from a wide range of fields. The Instructables posts provide complete documentation for building and utilizing the proposed devices, including bills of materials, embedded photos and videos, and source files.

Student teams also presented their research and demonstrated their devices at a university-wide **undergraduate research symposium** at the conclusion of the semester (Figure 1). In addition to fostering oral

Year Two (Spring 2020)

Week		Studio Topics	Corresponding Assignment
1		Project Introduction + Design Process Overview	Skills + Project Interest Survey (Due Week 2)
2		Working on Group Dynamics	Group Assessment Rubric (Due Week 3) Project Proposal (Due Week 3)
3		Design Brainstorm Activity	Preliminary Design Review (Due Week 5)
4		Group Work Time + Check-Ins	
5		Preliminary Design Presentations	First Prototype (Due Week 7)
6		Group Work Time + Check-Ins	
7		First Prototype Demonstrations	
8	Planned	Developing a Testing Plan + Device Demonstration	Testing Plan (Due Week 9)
		Classes cancelled due to COVID-19	
9	Planned	Group Work, Check-Ins	Testing Results (Due Week 10) Updated Design (Due Week 10)
	Actual	Updated Class Expectations + Prototype Reflections	Prototype Reflections (Due Week 10)
10	Planned	Testing Results + Updated Design Presentations	
	Actual	Computational Analysis	Simulation/Analysis (Due Week 12)
11	Planned	Final Deliverables	Symposium Demo (Due Week 13) Final Blog Post (Due Week 13) Instructables Post (Dues Week 13)
	Actual	Explaining the Request for Proposals	
12	Planned	Final Check-In	
	Actual	Explaining Visual Abstracts	The Request for Proposals (Due Week 14)
13	Planned	CURE Symposium	
	Actual	Final Check In	Group Assessment (Due Week 14) Visual Abstract (Due Week 14)
14			

Table 2: Spring 2020 semester timeline for R&D Studio sessions and assignments.

presentation acumen among students, the symposium highlighted the growing impact of course-based undergraduate research opportunities at Brown, and generated multiple ideas for collaboration among educators and further integration of CUREs into the engineering curriculum.

A table of the topics of focus in the weekly "R&D Studio" lab session as well as the assignments throughout the semester are outlined in Table 1.

Course Redesign: From Year One to Two

In January 2020 (about seven months following the end of SP19, and two weeks prior to SP20), six students who had completed the CURE module in SP19 participated in a three-hour focus group to identify successes as well as room for improvements for the course, and to brainstorm changes that could be implemented to improve the course experience. As a result, the students collectively provided six specific suggestions for improvement. A summary of these suggestions, as well as the context around the suggestions and how they were addressed in the SP20 implementation, are described here:

1. *Project topics should be based on clearly defined needs and users.*
    a. **SP19**: A list of potential project topics was compiled by the instructors based on perceived interests and needs. Without a clear need and external user in mind for each topic, many of the project's goals ultimately lacked focus.
    b. **SP20**: Projects were solicited from research labs across the University in advance of the course. A total of eight projects that best aligned with the course scope were identified: four were identified from Mechanical Engineering faculty, two from Biomedical Engineering, one from Chemical Engineering, and one from Cognitive, Linguistic & Psychological Sciences. More projects topics were acquired than number of groups planned, to improve the chances for students to identify a project of personal interest. As part of the project proposal process, the faculty were made aware that there would be an expectation for them to advise and evaluate the group directly on at least three occasions throughout the semester as "Faculty Mentors". The course instructor met with each of the potential Faculty Mentors to review expectations and to refine the project scope prior to the semester.
2. *Team formation should be based on interests.*
    a. **SP19**: The group formation survey focused exclusively on background coursework, personality traits, and skills.
    b. **SP20**: The group formation survey was augmented to include the pre-identified project topics described in the prior point. This al-

lowed groups to be formed based on interests, and as a consequence project topics were selected earlier in the semester.

3. *Instructors should meet with group members individually throughout the semester so that instructors could be made aware of interpersonal group conflicts.*

a. **SP19**: No explicit or formal opportunities existed for students to provide feedback to the course instructor on their group dynamics and other team member progress.

b. **SP20**: A midterm and final intra-group evaluation (developed at the beginning of the semester by the groups themselves) provided an opportunity for students to share feedback on group members in a confidential setting.

4. *Undergraduate Teaching Assistants (UTA) should be assigned to each group.*

a. **SP19**: Undergraduate TAs were not assigned to specific project groups, but rather held open office hours for all groups. Consistent feedback from both students and TAs indicated that this resource was rarely utilized.

b. **SP20**: Each student group was assigned an UTA mentor. These students were all graduates of the SP19 course and thus were familiar with the course paradigm. The UTA closely monitored group progress, helped identify and address group dynamic and technical challenges throughout the semester, and served as a liaison between the Faculty Mentor and the group for scheduling. The overall instructor met weekly with the TA staff to review progress.

5. *More time should be provided for meetings and informal interactions with the instructors.*

a. **SP19**: Nearly each week, a prescribed lesson and interactive assignment was presented in the R&D Studio. While providing some necessary background, the structure only allowed for minimal open-ended interactions with the instructors.

b. **SP20**: Overall structured assignments in the studio were reduced, and replaced with frequent "check-ins" where the instructor could meet with the groups individually and engage in a highly collaborative manner.

6. *Additional technical resources for providing background on selected project topics are needed.*

a. **SP19**: Potential project topics were determined by the instructional staff, and students were asked to perform the necessary literature review following general guidance on best practices.

b. **SP20**: Faculty Mentors were asked to provide each group with three key pieces of literature to establish the requisite background. Faculty Mentors also served as a direct resource for additional technical questions about the topic.

Year Two

As discussed in the prior section, project topics were solicited and curated by the instructor in advance of the course. The group formation survey was revised to allow students to rank their interest in the identified project topics. Groups were assigned taking interests into account as much as possible, with the condition that each group would be responding to a different project topic. The original intention of the revised course module was to maintain the prior final deliverables (Final Blog Post, Instructables Post, and Symposium Demonstration) while modifying the precedent course structure as described in the prior section. Unfortunately, the COVID-19 pandemic abruptly eliminated the possibility of continuing the physical aspects of the project approximately halfway through the semester. At the point of transition to virtual learning, the students had just completed and presented their initial prototypes.

Since iteration on the prototype could not continue, the students continued their line of research using commercial computational fluid dynamics software (COMSOL) that they were learning to use as part of the lecture portion of the course. The students worked with the instructor and faculty mentor to identify an open research question that they would address via **simulation** to inform future design efforts.

The final deliverable was then converted into a response to an instructor-generated **Request for Proposals**. This assignment provided the students with the opportunity to synthesize their preliminary experimental and numerical work into a single coherent story or pitch, as well as propose a management and technical plan should they continue the research.

Students were also asked to prepare a **Visual Abstract** of their research in the form of a single-page summary of their work presented in a broadly accessible and visually-oriented format.

Table 2 includes the course plan for year 2, as well as the modified course plan in response to the COVID-19 pandemic which necessitated a transition to remote learning following week 7.

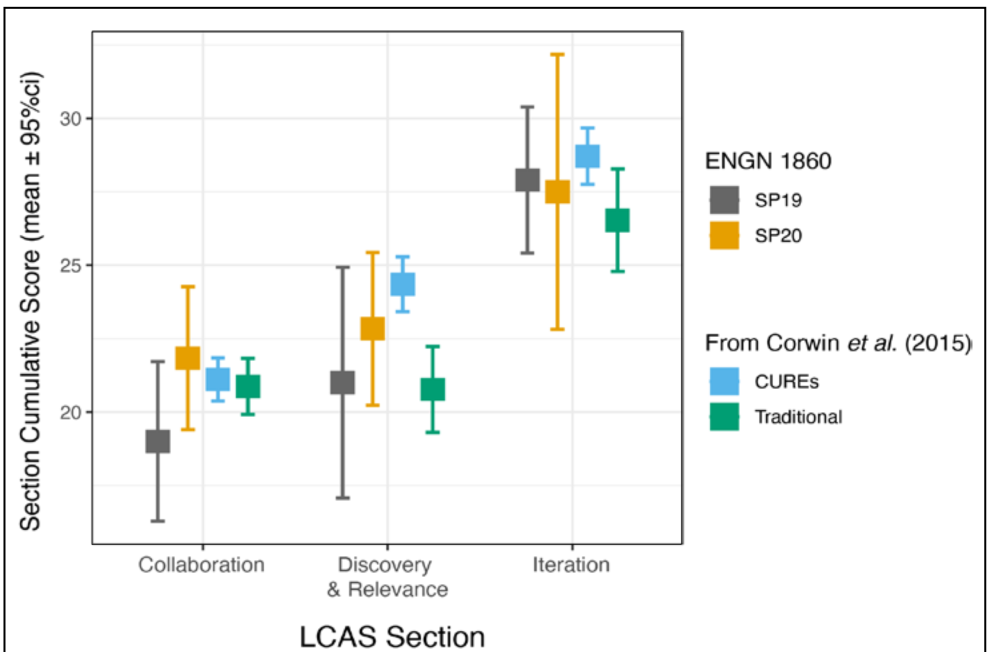

Figure 2. Results of Laboratory Course Assessment Survey. LCAS section scores plotted as means with 95% confidence intervals. Our data from Spring 2019 (SP19, N=9), and Spring 2020 (SP20, N=7) are plotted alongside scores from CUREs and traditional labs reported in Corwin *et al.* (2015). Although highly variable due to small samples sizes, our course trends toward an improvement in LCAS scores from year 1 (SP19) to year 2 (SP20).

Outcomes and Impact

Student outcomes

Methods for assessing student outcomes

To evaluate student outcomes, pre- and post-course surveys composed of questions from validated survey instruments were used. These surveys were independently administered and analyzed by individuals outside the course (through support from the Sheridan Center for Teaching and Learning at Brown). The Laboratory Course Assessment Survey (LCAS; Corwin *et al*., 2015) was used to evaluate CURE dimensions of the course. The LCAS assesses four of the CURE dimensions (Auchincloss *et al*., 2014) using three scales: Collaboration, Discovery & Relevance, and Iteration. As in Corwin et al. (2015), the LCAS was administered post-course. Questions from Hanauer *et al.'s* (2016) Measure of College Student Persistence in the Sciences (PITS survey) were utilized to examine affective outcomes.

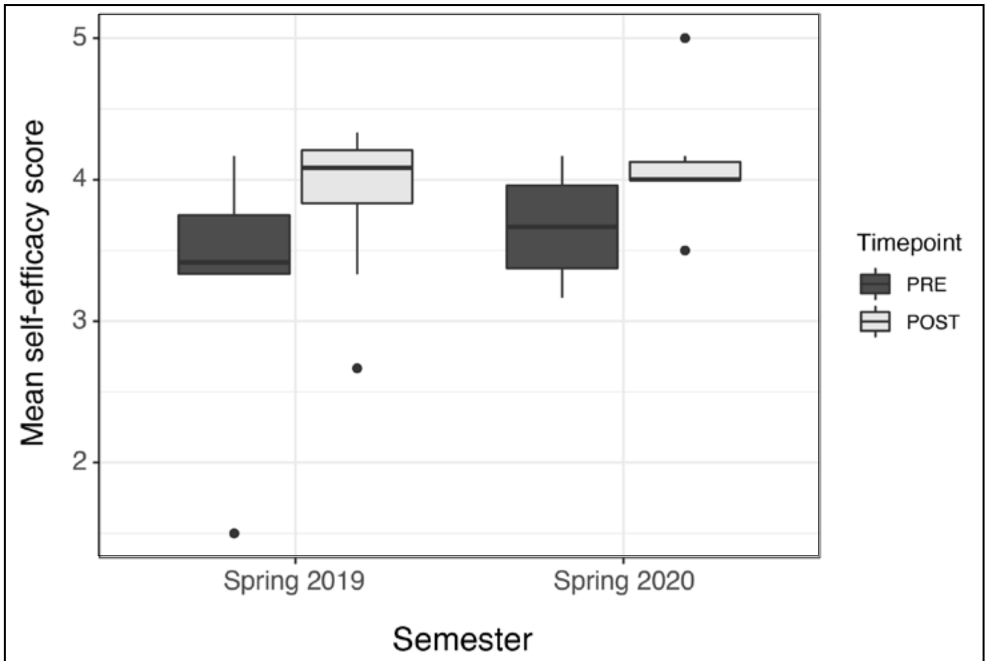

Figure 3. Positive outcomes in self-efficacy in both semesters. Students showed a significant increase in their self-reported self-efficacy scores between the two timepoints (Kruskal-Wallace rank sum test: $\chi^2 = 5.0132$, df = 1, $P = 0.02515$). There was no significant difference in scores between the two semesters ($\chi^2 = 0.097607$, df = 1, $P = 0.7547$). $N_{2019} = 8$; $N_{2020} = 6$. Boxplots follow standard Tukey representations: boxes represent the 25-75% interquartile range and median (center line) with outliers indicated by points.

The surveys were administered through Qualtrics and distributed to students via direct email. For questions that were administered pre- and post- course and utilized to examine change over the semester, only students who completed both the pre- and the post- survey were included. All data analyses were performed in RStudio (RStudio Team, 2020). The data were checked for normality using a Shapiro-Wilk test. None of the data were found to be normally distributed, so Kruskall-Wallace rank sum tests were used to compare means between groups. Brown University's Office of Institutional Research declared this project non-regulated, i.e., not meeting the federal definition of research.

Student Outcomes

Figure 2 shows LCAS scores from the two iterations of our course plotted with scores for CUREs and traditional labs reported in Corwin *et al*. (2015) for comparison. The sample sizes were too small to see a statistically significant improvement in CURE elements over the two years, however, there is an apparent positive trend from year 1 (2019) to year 2 (2020), especially in the Collaboration and Discovery & Relevance subsections.

Results from the PITS survey questions showed a significant increase in students' self-reported self-efficacy over the course of the semester (Figure 3; Kruskal-Wallace rank sum test: $\chi^2 = 5.0132$, df = 1, P = 0.02515), but no significant difference between the two semesters. We did not observe any significant change in science identity over the semester, nor did we see a difference between years.

Student reflections and CURE characteristics

As discussed earlier, the course module was designed with the intention of incorporating all five characteristics of a CURE course (Auchincloss, 2014). In December 2020, 17 graduates of the course module were contacted by the instructor (including current Brown undergraduates, and Brown alumni in both graduate school and industry) and asked to reflect on their experience in the CURE module (R&D Studio). Below, we mapped excerpts of the students responses to corresponding CURE characteristics as evidence of having achieved these course design goals.

Use of disciplinary practices

- "The R&D studio allowed me the skills to take ownership of a project unlike any other engineering class I participated in at Brown. These skills, rarely taught in the standard engineering class, proved instrumental for both my capstone/thesis and post graduation job."
- "From a technical skills perspective, working with COMSOL was really beneficial, as FEA and CFD are really broadly applicable across the engineering industry."
- "I think that the manufacturing skills that I was able to build upon helped greatly for my capstone project. Problem-solving & critical thinking skills are also very beneficial. Being able to explore different approaches to a problem, and thinking of the methods that can answer potential research questions helped me in my UTRA [a traditional URE] project, for example."
- "The budget, user, feasibility, and design considerations are all very important aspects of engineering that are never really taught well in other engineering classes, and this design project helped me learn to work with all real-world aspects of an engineering project."

Discovery of an unknown outcome

- "It was up to us to determine the pros and cons of two methods and decide which one to proceed with in the final design. Additionally, it was up to us to balance the cost and performance. In short, giving the students the freedom to approach the problem from different angles let students tackle various research problems which were unlike other engineering courses."
- "The project was structured to supply just enough instructor/TA involvement to give students creative freedom while still offering guidance for novices."

Broadly relevant research

- "The most appealing aspect of the R&D studio for me was the fact that I had the chance to apply the theoretical knowledge that I was receiving through my studies in a real world problem."
- "I remember being very motivated because we were deeply involved with the project every step of the way. The fact that it could be used by professors in their research added to the excitement as well."
- "I think the one aspect of the R&D studio that distinguishes it the most from other engineering classes was how hands-on it was and directly applicable to a research lab on campus. In many other classes, projects are either more theoretical or do not have an impact anywhere outside of class."
- "The projects themselves were designing for an actual use case and filling a need of a lab on campus, which was really engaging and worthwhile. Many short-term class projects or labs are limited in scope and applicability, so it was really cool to be able to work on a project that was realistic with the end goal of it being used in the future, rather than following instructions to create an idealized experiment for the sake of illustrating a concept."

Collaboration

- "The collaboration with a team of students striving for a unified goal over the course of one semester distinguished this course model from any other engineering class I have taken."

- "I also remember how it made me feel like more of a part of the Brown Engineering community, especially during the project presentations when the whole class and the professors of the labs were all there."
- "Listening to the customer's requirements, evaluating them and finding ways to implement them, keeping the customer up to date with our progress as well as presenting our ideas helped me improve my communication and presentational skills."
- "I was introduced to methods in order to effectively work as a team in order to complete an engineering project. I remember partaking in several group building activities on how to evenly divide workload and what to do in case of in-group conflicts. I believe that this is an important skill to develop and will be useful in all kinds of settings in the future."
- "Learning when to take on a leadership role and assign tasks versus when to let others lead and assign tasks was a very useful experience for me."
- "The R&D Studio enabled a more collaborative and friendly environment that extended outside of the project."

Iteration

- "While some classes have project components, they are rarely on a scale that requires students to holistically develop their engineering design skills such as iterative design, prototyping, manufacture, and testing. This class dedicates a large portion of the course work to a significant design cycle which forces students to learn new skills and knowledge independent of class work as well as prototype, build, and test a physical system."
- "Even before the pandemic had a significant impact on the project, our requirements shifted quite a few times, so doing problem-solving based on the changing design and issues we ran into will be really useful in the future."

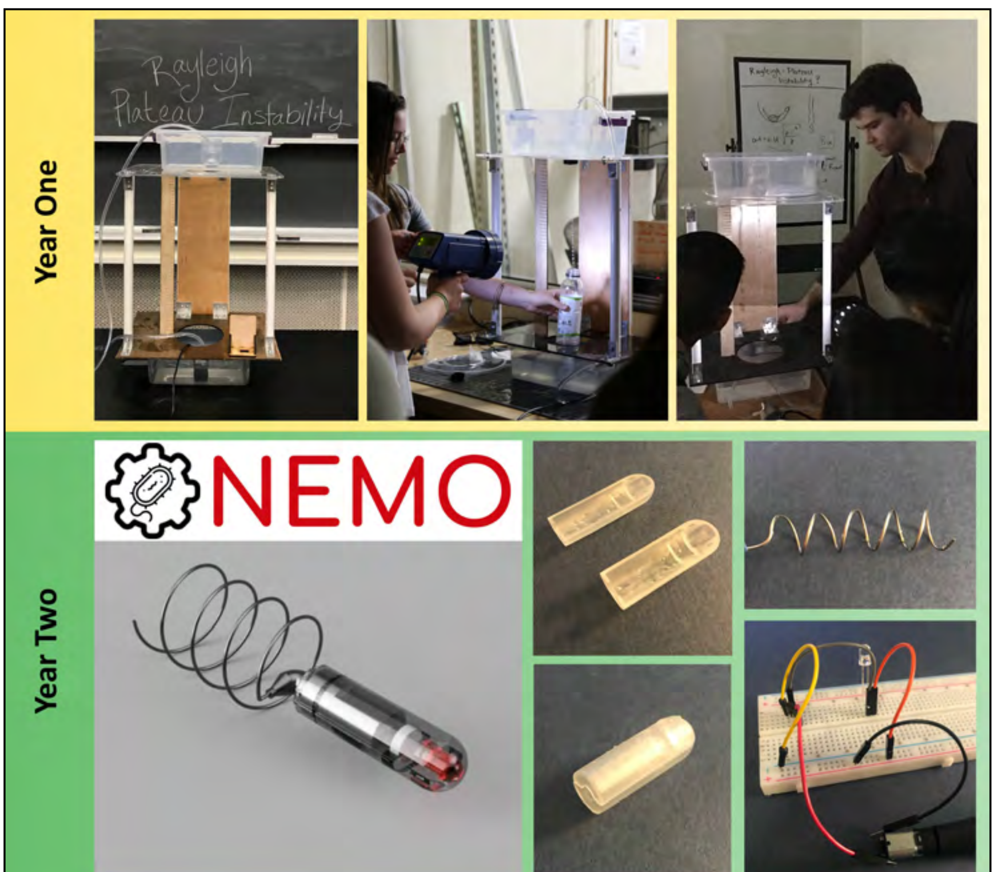

Figure 4: (Top Row) Sample Project Year 1. Rayleigh-Plateau demonstration device (left) developed in SP19 was used at two outreach opportunities for high school students at Brown University: Girls Get Math 2019 (center) and STEM Day 2020 (right). (Bottom Row) Sample Project Year 2. Project deliverables from SP20 for the "NEMO" robotic swimmer research project that has since been continued with undergraduates and the faculty mentor beyond the course context.

Broader impact

Year One

Upon publication, several of the "Instructable" posts were selected to be "Featured" on the Science landing page for Instructables Workshop, garnering thousands of views from the community within the first few months of their release. As of December 2020, the four instructables posts produced by the student groups in SP19 have been collectively viewed over 12,000 times, with one of the posts having over 6,000 views.

Promotion of the course products on social media also resulted in a positive response from the fluid dynamics community, resulting in discussion of implementation of similar design modules into fluid dynamics courses at other institutions. In particular, these projects were "retweeted" by a top fluid dynamics communication blog (@fyfluiddynamics) who reiterated one of the key novelties of the SP19 implementation: "Don't just see what the students did - they give you instructions for recreating their set-ups!" This post highlights one of the key novelties of the course (and of the resulting research products): the students were not only tasked with solving a problem but also with openly sharing their design. Social media platforms can potentially be used in future iterations of the course to promote individual projects in real time and gather feedback and suggestions, further involving students in the broader academic research community.

Furthermore, one of the physical demonstrations developed by the students was used directly in two outreach opportunities at Brown that engage high school students in STEM activities: the Girls Get Math program (2019) and STEM Day (2020). Undergraduate students designed and performed the outreach activity as depicted in Figure 4 (top row).

One student, in their reflection on the Spring 2019 course noted that: "The R&D Studio was one of my first research opportunities, and it played a large role in my decision to continue my education as a graduate research student." As the course continues, we hope to continue to track the impact it has on undergraduates' desire to pursue advanced degrees.

Year Two

SP20 was more recently completed, so many of the impacts remain to be seen. Furthermore, the initial course plans were disrupted by the COVID-19 pandemic which has significantly limited students returning to campus and engaging in on-campus activities.

At the end of the semester, all continuing students were asked to contact the instructor independently if they were interested in continuing the project in the following academic year. Seven of the eight continuing students responded, and expressed interest in resuming the research in either a follow-up course or as a traditional mentored research opportunity.

Despite the unanticipated challenges presented by the COVID-19 crisis, one project from Year Two resumed immediately in the Fall 2020 semester under the supervision of the Faculty Mentor for that group (see Figure 4, bottom row). These undergraduate research students are now directly integrated into the Faculty Mentor's research group to continue to pursue the project activities. The Faculty Mentor anticipates this effort will lead to peer-reviewed publication of the research in an open-access platform. This particular example of project continuity, while of course limited, does support the hypothesis that integration of research work into the standard curriculum has the potential to provide prolonged mutual benefit for both the students and faculty, while also generating new opportunities for students to become integrated in rigorous academic research.

Discussion

Relationship with Project-Based Learning

Project-Based learning (PBL) has documented benefits similar to that of CURE courses such as enhancing diversity and inclusion, improving student motivation and retention, and development of technical skills (Nguyen *et a*l, 2019). The engineering CURE module described in the present work could be readily classified as an example of Problem-Based Learning, but with projects that are specifically defined by the needs of the *research community*, a previously underutilized source of impactful and engaging project topics in engineering. This unique aspect typical of a CURE course (i.e. the deliberate focus on *broadly relevant researc*h) facilitates the possibility of enhanced faculty engagement during the course and beyond. Previous work in other fields has shown that in addition to benefiting students, CUREs also provide benefits to faculty (Shortlidge *et al*. 2016, Shortlidge *et al*., 2017). The most frequently reported benefits include connecting teaching and research, enjoyment, contribution to promotion or tenure, and potential for publication or contribution to their research program (Shortlidge *et al*., 2016). When developing and implementing the Faculty Mentor structure in SP20, there was some concern that relying on faculty contributions outside of the traditional course would become burdensome for them. However, the opposite effect was observed during SP20: faculty regularly expressed a desire to be more engaged and have more contact with the project groups than what was initially asked of them. Had the projects not been aligned with their research activities and agenda, this type of voluntary engagement would be unrealistic to imagine in almost all cases.

Beyond the faculty, research-based learning (such as CUREs) may provide additional benefits to the students such as enhancing student interest in the pursuit of graduate degrees, ultimately enhancing diversity in the broader research community (Shaban *et al.*, 2015). Furthermore, the course structure described in the present work also establishes a novel mechanism for connecting engineering students and research faculty that can persist beyond the confines of a single semester course. In typical mentored research experiences, the onus falls on the student to approach a faculty member, which can be intimidating especially among STEM disciplines (Bangera *et al*., 2014). This barrier to students is intensified among some identity groups which are underrepresented in STEM, such as students of color, women, and students with lower levels of confidence (reviewed in Bangera *et al.*, 2014). In fact, first-generation college students and students from lower socioeconomic status households are less likely to communicate with faculty, either via email or in person, compared to their peers from higher socioeconomic status or with college educated parents (Kim & Sax, 2009). Because our course design facilitates the connection between faculty mentors and student groups, it provides an additional stepping stone into mentored research where barriers associated with approaching a professor are greatly reduced.

Overall we expect the CURE model in engineering to be complementary to the more traditional PBL opportunities in present curricula, but with potential additional benefits made possible through enhanced student-faculty engagement.

Barriers to Implementation

The implementation of such a course is not without barriers, although some are common to any project-based learning course. First, there is an additional financial cost due to materials and additional personnel associated with the course. In the present example, the development and implementation of the redesigned course module was made possible by external funding from the HHMI. Furthermore, campus resources (such as the makerspace) were specifically leveraged to make the course module practical and affordable. Second, we have observed that the success of the course relies heavily on appropriate identification of project topics. At teaching-focused institutions with fewer or smaller research labs, this could be considerably more challenging. External faculty engagement may also vary unpredictably, creating the potential for unbalance between groups. Lastly, this model would be challenging to readily adopt to larger class sizes. By design, the project topics may extend over many disciplines within a single semester, and then change again in following semesters. It is anticipated that the overall management and oversight of the course with such specialized topics would be increasingly challenging for larger enrollments. An appropriate hierarchical course management scheme is essential, even in a course of the present size (3-4 project groups total), due to the highly specialized and unpredictable nature of research. In the present implementation, undergraduate TA mentors monitored each group's progress regularly while a head TA organized the weekly studios and provided administrative support (such as material ordering). Progress and potential roadblocks for each group were reviewed in a weekly meeting of the instructional staff.

Future Improvements

There are several ideas we aim to explore in future versions of the course to further improve the overall experience and its efficacy. In particular, we aim to solicit an increased number of projects outside of the students' core discipline (in this case, Mechanical Engineering). To this end, students will then have the opportunity to work in a more interdisciplinary setting and operate as the "expert" of their discipline. We hypothesize that more substantial improvements in students' confidence will result and their ability to communicate technical topics and findings to a broader audience will also benefit. Having a broad range of projects from other disciplines will expose all students to a broader range of practical applications in the field, while also highlighting the increasingly interdisciplinary nature of research.

In the SP20 course, it also became apparent that more clearly defined roles and boundaries from the student groups and faculty members need to be developed. Rather than actively seeking out the Faculty Mentors' help, students regularly felt uncertain how such engagement would be viewed in terms of the course grading and expectations. Of course, it is not realistic (or desirable) for research to be completed in isolation, but some autonomy for the groups should be preserved to allow the students to develop a sense of independence and ownership of the project. Clearly a thoughtful balance and perhaps even a group-dependent approach is required in future iterations of the course. It is anticipated that relying more on Faculty Mentors outside of the students' discipline may help naturally impose such boundaries.

In future work, we also intend to develop a standalone engineering course with a similar framework which will allow for enrollment of students with broader backgrounds to be engaged in course based engineering research activities. Without a traditional lecture component to the course, significantly more time can be dedicated exclusively to the project. The intention, however, is to maintain this as predominantly a second or third-year course in the curriculum. It is important that students develop some theoretical knowledge in engineering before or in parallel with the course so that they can practically apply the "engineering science" in the engineering design process while tackling an open-ended problem. This is often a cited goal for "senior capstone" courses, but generally comes too late in the curriculum to be impactful on students' professional trajectory and is also largely irrelevant to retention in engineering.

Further quantitative pedagogical evaluation is needed on the course and broadly for implementations of CUREs in engineering. Given the relatively small sample size thus far, quantitative trends are difficult to isolate with confidence. Increasing the enrollment and number of implementations will allow for more quantitative assessment and validation of the hypothesis presented herein and will guide future developments.

Conclusions

In summary, we have outlined a course-based research experience (CURE) module as implemented in an upper-level engineering course at Brown University. The semester-long research project allowed students to engage in an open-ended and real-world project sourced from the needs of the research community and to share their findings broadly. Quantitative assessments of the course module demonstrated significant improvement in student's perceived self-efficacy throughout the course. The course module described here is only a single example of how one might engage students in research activities directly in the engineering curriculum. Our hope is that the present work will inspire other engineering educators to begin to design research activities into their own courses in increasingly unique and efficacious ways as has been the case in other fields.

The CURE model in engineering has great potential to realize the benefits of CUREs now well established in other scientific fields. In particular, by increasing the accessibility of research opportunities for all students we may ultimately foster a more diverse community of individuals interested in pursuing graduate studies and research in engineering.

Acknowledgements

This work was funded by an HHMI grant (#52008092, Program Director, Mark Johnson) to Brown University, and the Hibbitt Postdoctoral Fellowship administered through Brown's School of Engineering. We also gratefully acknowledge the support and engagement of the Brown Design Workshop, the Sheridan Center for Teaching and Learning, the faculty project mentors, and all of the students and teaching assistants who participated in the course.

Students provided written permission to share project content, photographs, and course feedback (whenever applicable).

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