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Innovations in Remote Teaching of Engineering Design Teams

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Eric Seibel (he/him) received his PhD in Bioengineering at the University of Washington in 1996 after working four years in the medical device industry and receiving his BS and MS degrees in Mechanical Engineering from Cornell University and University of California at Berkeley. As a research professor in the mechanical engineering department at the UW, Dr. Seibel has been teaching medical device design in an interactive classroom environment for over 5 years and advising student research in biomedical instrumentation for over 20 years. Dr. Seibel has published widely and co-authored 50 issued US patents, many having been licensed to the medical device industry from the UW. Dr. Seibel is director of the Human Photonics Lab and affiliated with the departments of bioengineering, electrical & computer engineering, and oral health sciences at the UW.

Shayla Payne

Shayla Payne (she/her) completed the EIH program as an undergraduate student in 2020, when the program transitioned to remote with the onset of the COVID-19 pandemic. She continued her involvement in EIH as a teaching assistant while completing her master's degree in the mechanical engineering department at the UW. Incorporating her experiences as a graduate student during a pandemic and an alumni of the EIH program, Shayla helped to introduce new tools and methods allowing the EIH program to adapt and excel in a virtual setting. Currently, Shayla is a mechanical engineer at Dexcom designing the future of health monitoring systems.

Innovations in Remote Teaching of Engineering Design Teams

Abstract

The University of Washington's Engineering Innovation in Health program is a yearlong engineering design course sequence where senior undergraduate and graduate engineering students across different disciplines work in teams with health professionals to address their unmet needs. With the onset of the COVID-19 pandemic, these team- and project-based courses shifted from an in-person to remote course environment. Here, we share innovative teaching strategies for a team-based, remote course environment. We show how this shift affected productivity by comparing survey results from before (in person) and during (remote) the pandemic. Preliminary results show that overall project outcomes and productivity were as high or, in some cases, higher during the pandemic than prior to the pandemic. These findings suggest that the innovative remote teaching strategies implemented by the teaching team provided effective options in the absence of certain hands-on experiences that are considered critical to engineering capstone design courses. A discussion on these teaching strategies in the context beyond the pandemic are considered in the discussion.

Introduction

Engineering capstone design courses provide students with a team-based project experience in addressing an open-ended, real-world, unmet need. In the Engineering Innovation in Health (EIH) capstone design program at the University of Washington (UW), multidisciplinary student teams design, construct, and test a technical innovation to address a pressing unmet need proposed by a health care professional [1], [2]. During this process, they investigate a holistic range of factors that contribute to the project's development and impact (*e.g.*, stakeholders, existing solutions, market opportunity, intellectual property, regulations, and reimbursement).

Much of the learning in capstone design courses occurs outside the classroom environment through hands-on and typically on-site experiences, which are forms of active and student-centered learning [3], [4]. For example, students may shadow or observe stakeholders on the job as part of the exploration process of design [5], or they may use maker spaces, tools, and equipment to construct, test, and evaluate prototypes.

Due to the onset of the COVID-19 pandemic caused by SARS-CoV-2, the EIH capstone program shifted to a remote learning environment during the winter quarter of 2020, in which a combination of Zoom, Microsoft (MS) Teams, and other online tools were used to deliver course content and to facilitate meetings. The sudden shift to remote environment necessitated quick adoption of innovative teaching approaches to ensure students were provided with high-quality alternatives to the hands-on, in-person experiences that were suddenly unavailable. Here, we share some of these strategies and show how this shift affected productivity by comparing longitudinal team survey results from before and during the pandemic. Preliminary results show that overall project outcomes and productivity were as high or, in some cases, higher during the pandemic than prior to the pandemic. These findings suggest that the innovative remote teaching strategies implemented by the teaching team provided effective options in the absence of certain hands-on experiences that are considered critical to engineering capstone design courses.

Background

Engineering Innovation in Health (EIH) is a three-quarter (9 month) longitudinal academic program in the College of Engineering at the UW that promotes interdisciplinary collaboration between engineering and the health sciences [2]. Founded in 2013, the focus of this capstone program is to develop innovative technical solutions to pressing clinical and translational health challenges. Undergraduate and graduate students across engineering disciplines (*e.g.*, mechanical, electrical, biomedical, chemical, and materials science) are partnered with health professionals (*e.g.*, physicians, nurses, dentists, therapists, pharmacists) to solve unmet health challenges. In the first quarter, teams of 3–5 students work closely with the health professional(s) who originally proposed the unmet health challenge to develop a deep understanding of the unmet health need, including potential markets, stakeholder psychologies, prior solutions, intellectual property considerations, regulatory requirements, and reimbursement strategies. In the second and third quarters, the teams continue to refine and iterate upon their understanding of the unmet need and develop a series of functional prototypes (which are quantitatively evaluated) and an early-stage business plan.

The program faculty observed that teams that appeared to be organizationally high-functioning (*e.g.,* teams that set and achieved milestones, and addressed challenges in ways that did not lead to interpersonal conflicts) had better engineering outcomes (*e.g.,* quality of innovation, measurable outputs). For these reasons, the teaching team introduced team science approaches into the EIH program. Team science is defined as "a collaborative effort to address a scientific challenge that leverages the strengths and expertise of professionals trained in different fields" [6]. This innovative model for integrating team science training within an existing biodesign education program was previously described, along with preliminary evidence of effectiveness [2]. The team science model for the EIH program and evaluation activities were adapted from the pre-pandemic learning environment to the remote-learning environment instituted during the pandemic, allowing for comparison of outcomes before and during the pandemic.

Methods

Previous course adaptations around team science were made and tracked by the teaching team during each of three academic years (Y1: 2018–2019, Y2: 2019–2020, Y3: 2020–2021) [2]. Impacts of adaptations on team functioning and outcomes were evaluated using semi-structured surveys (**Appendix A**) that were deployed to students in the program at the beginning and end of each academic year. All study activities were carried out in accordance with approved ethical guidelines and were deemed exempt by the institutional review board at the UW.

Course Adaptations

Tools Used to Facilitate Remote Education. Multiple online tools were used to facilitate a remote classroom. Zoom was used to host lectures, team meetings, and presentations. MS Teams was used as a virtual classroom forum where announcements and files could be shared for the whole class, as well as for individual student teams, where each project team had its own channel. Poll Everywhere (PollEv) was used as an interactive tool during class to poll students and ask open-ended questions. Google Docs or Google Sheets were used during breakout rooms in Zoom as a living worksheet (*i.e*., multiple students could edit the document simultaneously and see updates in real-time).

Remote Teaching Approaches Implemented During the Pandemic. Existing course activities were preserved in the curriculum but modified for effective delivery in the remote learning environment. For example, lectures covering specific engineering design concepts were delivered synchronously (*i.e.*, in real-time) over Zoom, and questions or feedback were taken synchronously throughout or after the presentation, or otherwise facilitated using Zoom's chat function. The presentations were often recorded so students could return to the lecture material throughout the quarter. **Table 1** provides additional examples of existing course activities and the modifications for the remote course environment.

Table 1. Existing course activities that were modified for a remote course environment. A more detailed description of the activities can be found in [2].

Activity	Description	Modifications	Ref.
Lectures	In-person delivery of engineering design course content.	Synchronous presentation over Zoom with Q&A facilitated using the chat function. Presentations were recorded for students to return to the material.	
Office hours	Faculty and students meet outside of class to discuss course material.	Virtual office hours held using Zoom or MS Teams.	
Impromptu networking	Pairs discuss a prompt (60 seconds per individual) and repeat two more times with a new partner.	Virtual breakout rooms with new pairs for each round.	[7]
Welcome Letter	A letter drafted and signed by all teammates to develop shared team goals, team agreement, communication plan, and contingency plan for addressing potential challenges/conflicts.	Ensure a remote meeting and communication plan is included in the letter.	[8]
Shift-and-share presentations	A group of teams present simultaneously to a rotating small audience, then repeat presentation until audience members have rotated through all presentations. This is repeated for another group of presentations until all teams have presented to every team.	Audience members are split across virtual breakout rooms where they remain, while a group of teams repeat their presentations as they rotate through breakout rooms.	[7]
1-2-4-all	Self-reflection to a prompt (1 min.), paired discussion (2 min.), group discussion (4 min.), report out to large group (5 min.).	Breakout rooms for each grouping and PollEv to help facilitate large group report out.	[7]
Peer feedback	Each student provides peer feedback on at least two other team presentations.	An online survey tool (e.g., Google Forms) is used to collect peer feedback.	[9]

Beyond modifying existing course activities, the teaching team introduced new course activities specific to the remote environment. Some activities were introduced to provide the sense of community and camaraderie that is cultivated in the class but often limited in remote settings. For example, a welcome activity was displayed as students entered every class, such as a fun survey or interactive poll (*e.g.*, "What is your hidden talent?"). Other activities were introduced to facilitate active learning. For example, as students dispersed into breakout rooms to apply new course content to their projects, they were asked to complete an online worksheet (created using a tool such as MS Teams or Google Docs) that could be edited simultaneously by multiple users. Sharing a single document that all teams could work on in their breakout rooms was an interactive and collaborative approach that facilitated team member participation and attainment of a common understanding. It also made it easier for instructors to track what was happening in breakout rooms and to offer support and clarification when teams encountered challenges. **Table 2** provides additional examples of new additions to course activities and how they were implemented in the remote course environment.

Table 2. Newly added course activities for the remote course environment.

Activity	Objective	Description
Welcome activity	Build community and camaraderie in the remote classroom.	Open each class with an engaging activity or interactive poll (*e.g.*, What is your hidden talent?).
Online worksheet	Collaborative and interactive approach that facilitated participation by all team members. Instructors may monitor breakout room activity at a quick glance.	Students work simultaneously on an online document as a team during breakout sessions.
Student contributions	Show evidence of individual student contributions and allow students to take ownership of their roles and responsibilities. [10]	For each assignment submitted, teams describe an individual's contributions.
Prototyping competition	Teach lean prototyping skills (*e.g.*, using materials that can be found at home or hardware store).	Students developed prototypes around a simple design example and created videos to demo the prototype and address simple evaluation questions. A competition was held during class to motivate students and encourage participation.
Virtual tours	Provide students with an immersive "real-world" experience in engineering design.	Clinicians and industry professionals prepared a synchronous ("live") or pre-recorded video sharing their day-to-day job experience.
3D printing service	Provide students with prototyping resources despite lack of access to prototyping lab facilities.	3D prints were generated and shipped out to students.
Class debrief	Close each class with a shared sense of community.	Wrap up each class with 5–10 min debrief of common questions or concerns that arose.

Evaluation

Surveys were distributed to all students enrolled in the EIH class for the Fall and Spring quarters each year from Fall 2018 to Spring 2021 (three academic years). The surveys included questions about student demographics, previous experience in teams, feedback on course adaptations, and project outcomes and challenges. The fall and spring survey questions are provided in **Appendix A**. Quantitative data was analyzed using descriptive statistics, and short-answer qualitative data was analyzed using thematic analysis [11].

Results and Discussion

Demographics of Student Participants

A summary of the student demographics is shown in **Table 3**. We found that different demographic cohorts had similar group-project experiences prior to participation in the program (*e.g.*, high school, engineering and non-engineering classes at the college level, and work or volunteering activities, **Appendix B, Table 1**). Approximately 25% of students in each demographic cohort had worked on 1-2 engineering group projects in the past, 60-70% had worked on 3-4 engineering group projects in the past, and the remaining students had no prior group engineering project experience (**Appendix B, Table 2**). This similarity in prior experiences across the student cohorts suggests that comparisons across cohorts are appropriate. Table 3 also indicates the physical learning environment for each year (*i.e.*, in-person or remote due to the pandemic). Note that in Y2 (2019–2020), the switch to remote learning environment took place in March 2020, when the World Health Organization declared the novel coronavirus (COVID-19) outbreak a global pandemic.

Table 3. Summary of students surveyed, including total students enrolled, survey response rate, preferred gender affiliation (blue columns) and educational program (yellow columns), as well as learning environment (green columns). Note the change in student enrollment numbers between the fall and spring surveys is attributed to a down-selection of student participants by application and instructor selection and projects occurring in the program between the fall and winter quarters.

				Gender affiliation				*Educational program*			*Learning environment*	
Study Year	**Academic quarter**	**Total students enrolled**	**Survey response rate (%)**	**Male (%)**	**Female (%)**	**Non-binary (%)**	**Prefer not to say (%)**	**Undergrad (%)**	**Grad (%)**	**Other (%)**	**In-person**	**Remote**
Y1, 2018–2019	Fall	53	96	66	32	0	2	70	26	4	x	
	Spring	30	100	67	27	0	6	47	47	6	x	
Y2, 2019–2020	Fall	62	89	73	25	0	2	62	36	2	x	
	Spring	32	88	67	25	4	4	87	13	0		x
Y3, 2020–2021	Fall	65	92	62	33	2	3	75	25	0		x
	Spring	32	75	59	41	0	0	72	23	5		x

Student Perceptions of Remote Learning Activities

Surveys administered during the pandemic included questions related to remote activities and tools. Students were asked at the end of Y2 and Y3 (pandemic years) to indicate the extent to which remote activities and tools assisted the project team to become more efficient (*e.g.*, well-organized, minimum wasted effort, reaching milestones in a timely manner), effective (*e.g.*, successful in producing a desired or intended result, completing milestones), and successful in carrying out the project together. **Figure 1** shows a visual comparison of the student responses on a 5-point Likert scale from "not at all helpful" to "very helpful" and shows that a majority of students found the remote activities and tools to be moderately to very helpful, especially in Y3. Note that no comparison before and during the pandemic is provided as questions related to remote activities and tools were not asked in pre-pandemic surveys.

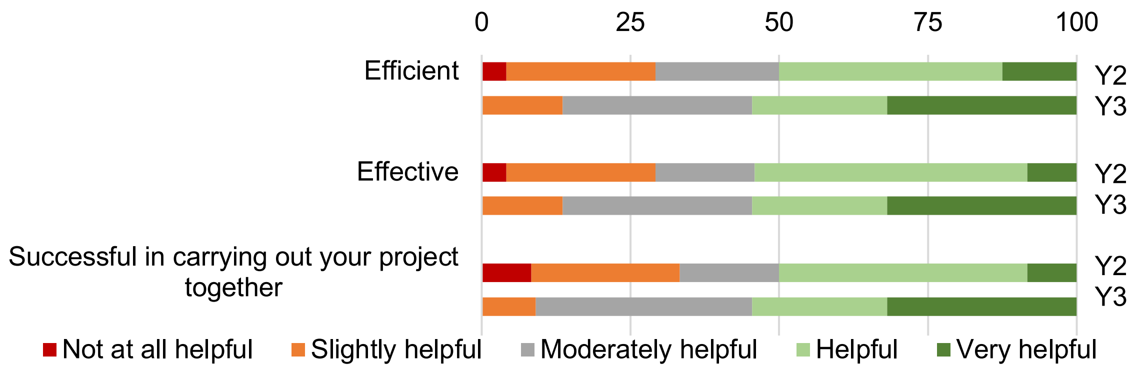

Figure 1. Student survey data reporting the extent (0 to 100%) to which the remote activities and tools helped EIH capstone teams to become more efficient, effective, and successful in carrying out the project together. Y2 responses are shown in the upper rows and Y3 responses in the lower rows. Responses are based on students reporting the level of helpfulness on a 5-point Likert scale (*i.e.*, not at all helpful to very helpful). Note: the shift to remote learning occurred midway through Y2.

Expected and Completed Project Outcomes

When the spring surveys were administered during the last class meeting of the year, students were asked to report on the likelihood to participate in certain activities related to their capstone project (*e.g.*, submit a patent application, submit an IRB application, etc.). Response options ranged from unlikely, neutral, likely, already in progress, or completed. **Table 4** shows the results of a subset of responses to the statements and the changes in the in-progress or completed status for each milestone from Y1 to Y2 and from Y1 to Y3. The full set of responses is shown in **Appendix B, Table 3**. Note that Y1 is a pre-pandemic baseline year in which students completed the entire year in-person. Thus, comparing results from Y1 to Y2 (ΔY2) show differences in the first year of the pandemic when the first half of the academic year was in-person and the second half was remote, and comparing results from Y1 to Y3 (ΔY3) shows differences between the fully in-person vs. fully remote versions of the course. ΔY2 values show a pattern of decline in most project outcomes except for three outcomes: continuing to work as a team after the end of the program (+8%); applying for grants, seed funding, or other sponsorship opportunities (+8%); and presenting the capstone project at conferences or other symposia (+10%). ΔY3 demonstrated increased productivity in making progress or completing most project outcomes for each of the outcomes that increased in ΔY2 (+25%, +21%, and +17% respectively). In addition, several other outcomes improved, such as submitting a patent application related to the capstone project (+12%); submitting an IRB application (or request exemption) to test device on human subjects (+25%); and obtaining press or media coverage of device (+1%).

Table 4. When the spring surveys were administered during the last class session of the year, students were asked to report on the likelihood to participate in certain activities related to their capstone project (*e.g.*, submit a patent application, submit an IRB application, etc.). Response options ranged from unlikely, neutral, likely, already in progress, or completed. Note that only the sum of responses for already in progress or completed are shown here and the full set of responses is shown in Appendix B, Table 3. For each project outcome listed, the difference (Δ) between Y2 and Y1 (middle column) or Y3 and Y1 (right column) is given for the "In progress or completed" values, where positive differences (indicating improvement in outcomes) are shaded in green and negative differences (indicating poorer outcomes) are shaded in red.

	In progress or completed	Y1, pre-pandemic	Y2, onset of pandemic	Y3, during pandemic
IP: Submit a patent application(s) related to your capstone project	%	24	13	36
	Δ		**-11**	**12**
IRB: Submit an IRB application to test your device on human subjects	%	6	4	31
	Δ		**-2**	**25**
Continue project: Continue to work as a team after the end of the program	%	0	8	25
	Δ		**8**	**25**
Seed funding or grants: Apply for grants, seed funding, or other sponsorship	%	0	8	21
	Δ		**8**	**21**
Presentations: Present capstone project at conferences or symposia	%	3	13	20
	Δ		**10**	**17**
Manufacturing: Manufacture your device to scale using intended materials	%	16	0	9
	Δ		**-16**	**-7**
Publish: Publish scholarly manuscript(s) related to your capstone project	%	13	0	8
	Δ		**-13**	**-5**
FDA: Seek FDA approval for your device	%	9	0	9
	Δ		**-9**	**0**
Press coverage: Obtain press or media coverage of your device	%	3	0	4
	Δ		**-3**	**1**
Form company: Form a commercial entity	%	21	0	0
	Δ		**-21**	**-21**

How Teams Were Affected by Working in a Remote Course Environment

In the spring surveys administered during the pandemic (Y2, 2020 and Y3, 2021), students were asked to respond to open-ended questions related to how their team and project were impacted by working in a remote course environment. Common themes that emerged from the student responses include challenges related to communication with teammates and difficulties accessing prototyping and testing resources (**Figure 2**). These are described in further detail with representative quotes from students for each theme. On the general shift to remote learning, a student reported, "It was hard. It became harder to enjoy time with the team because we couldn't joke as easily [as] in-person. It was less exciting because we couldn't see our physical products as easily."

Communication Challenges with Teammates. In the open-ended survey responses, students generally acknowledged that “these are unusual times” and that they “[tried] to accommodate each other whenever possible.” Yet, a range of communication challenges among teammates were reported. According to one student, meeting remotely “affected the quality of the discussion.” The student elaborated that device demonstration or a quick drawing around a prototype was difficult to effectively share with teammates. Other students reported that meeting remotely “made the experience less personal,” thus affecting the team’s motivation to work collaboratively. “I think [the emergence of the COVID-19 pandemic] affected us greatly, as we were not able to have in-person meetings and interactions needed to enable work to be completed efficiently.”[1]

Other communication challenges among teammates that were reported included geographical and time zone differences, especially when coordinating meetings and shipping items to one another, and personal and individual challenges affecting one’s ability to engage in coursework.

Difficulties Accessing Prototyping and Testing Resources. As part of working remotely, students were asked to work on prototypes at home. Prototyping resources were made available to students with department support (*e.g.*, shipping materials, supplies, and 3D prints to students’ homes); however, this often resulted in some students receiving more hands-on experience working with prototypes than others. For example, if a team had only fabricated a single working prototype, only one student was able to work with the prototype at a time before shipping or passing along to another team member. Some students perceived this as a positive learning opportunity, while others viewed compiling and testing the prototype as a burdensome, uneven distribution of workload. Those who were not as involved in the hands-on prototyping work reported disappointment and a sense of lost opportunity at missing out on the experience. On the other hand, those not involved in the prototyping work had the opportunity to contribute in other technical ways (*e.g.*, computational fluid dynamics analysis, finite element analysis, coding).

Most students reported at least some difficulties making progress on their prototypes or limited ability to perform testing. Prototyping lab and testing facilities were closed or restricted during Y2, and limited access was available to students during Y3 (*i.e.,* 1-2 students in the lab at a time due to physical distancing precautions). With closed (Y2) or limited (Y3) access to these facilities, students relied on ordering *ad hoc* supplies from online vendors, as well as using postal mail to ship parts to one another (costs were reimbursed by program funds). Global supply chain issues that arose during the pandemic also affected the students’ prototyping plans and activities. While some projects were more feasible to test in a home environment (*e.g.*, using standard scales or calipers), others required precision equipment or were more sensitive to the environment and thus not readily feasible to test at home. The instruction team prioritized student safety above project progress, and thus no expectation was placed on students to complete the prototype nor perform complex prototype evaluation at home.

[1] This quote was edited for grammar and clarity.

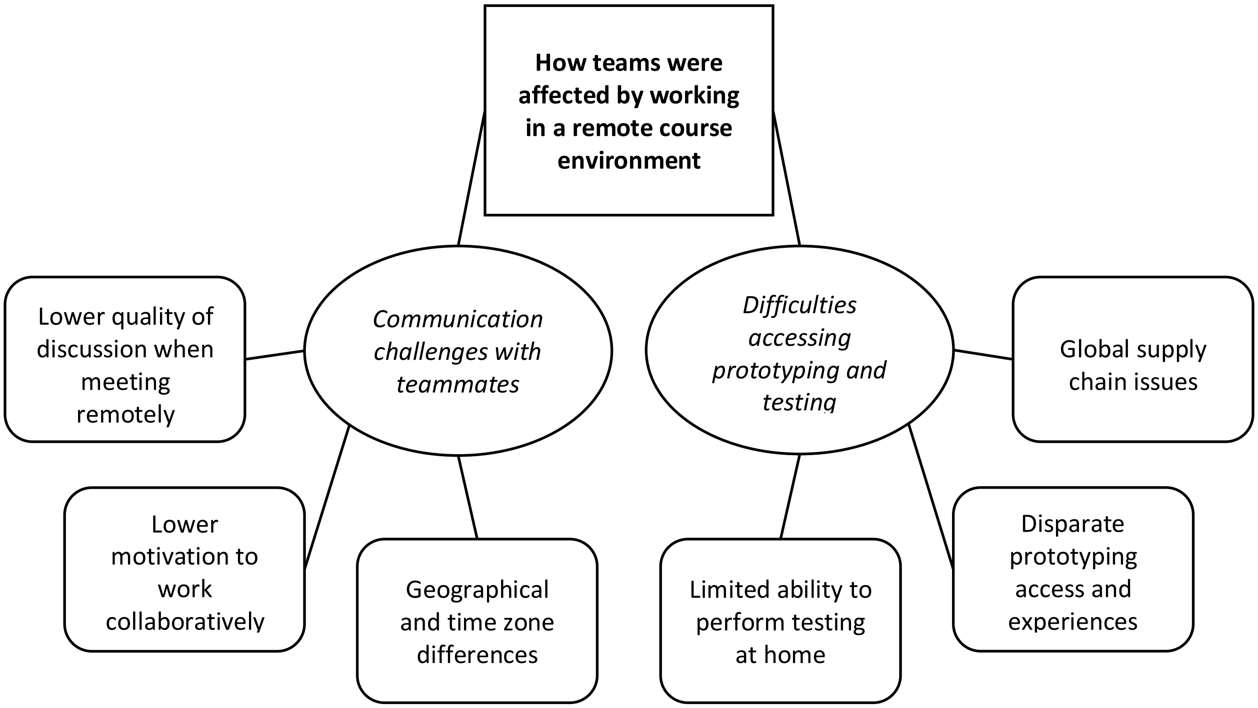

Figure 2. How teams were affected by working in a remote course environment.

How Teams Managed Working in a Remote Course Environment

Students were asked in the spring surveys to respond to open-ended questions around how their teams managed working in a remote course environment. Specifically, students were asked to share strategies and/or tools their team utilized (or increased use of) to manage working remotely as a team. Team strategies students reported included identifying weekly goals and deliverables to help with productivity and accountability, using multiple communication tools, and setting up recurring meetings when all team members were available. In moving away from in-person work and adjusting to remote work, students reported a larger emphasis on stakeholder interviews and secondary research (in lieu of on-site clinical observations and shadowing clinicians), as well as more simulations and modeling of experiments (rather than physical experimentation). The program instructors noted that students were interviewing significantly more stakeholders during the pandemic than in pre-pandemic years, when in-person meetings were more logistically challenging (*i.e.*, transportation, setting up a conference or meeting room, and scheduling around busy student and clinician schedules). Tools students reported as helping them to facilitate remote team work included Slack, Zoom, Trello, Microsoft Drive, Google Drive, MS Teams, Facebook Messages, and WhatsApp. Students also increased their use of modeling tools (*e.g.,* ANSYS for finite-element analysis or Simulink for model-based design) and simulation software (*e.g.*, Blender for computer graphics, Autodesk for computer-aided design, and MATLAB for computational analysis) in lieu of physical prototyping and experimentation.

Next Steps

Course faculty rapidly adapted the highly interactive, team-based capstone course to a remote learning environment following the onset of the COVID-19 pandemic. Existing annual fall and spring surveys that had been initiated prior to the pandemic to evaluate integration of team science training into the course provided a useful platform for evaluating the impacts of course adaptations made in response to the COVID-19 pandemic and the subsequent shift to remote learning. Quantitative results suggest that these adaptations were effective, and that overall project outcomes and productivity were as high, and in some cases higher, during the pandemic. Qualitative findings shed light on both the challenges that teams faced and their resourcefulness.

Altogether, the remote classroom activities and tools were reported to help teams become more efficient, effective, and successful in carrying out their projects together for over 90% of students in the first year of the pandemic (Y2), and for 100% of students in the second year of the pandemic (Y3) (Figure 1). Our interpretation of this difference is that students in the first year of the pandemic (Y2) started the academic year in person and were subjected to the rapid and unanticipated changes in the learning environment with the onset of the pandemic in March 2020. In contrast, students in the second year of the pandemic (Y3) came into the program with some familiarity with remote learning and experienced the entire year remotely. This may also have been the case for clinical partners, who became more familiar and comfortable with working remotely with teams by Y3. Reflecting on these changes in course delivery and improvements. In future years, the virtual lectures from Y3 will be continually improved and updated and presented in a flipped classroom experience, allowing more in-person team time to work on assignments, design, and prototyping [12].

Despite the circumstances and the challenges with remote learning for capstone education, students managed to make significant progress on their projects and reach key milestones by the end of the academic year (Table 4). Compared to pre-pandemic levels, more students planned to continue to work together as a team after the end of the program (8% increase for Y2 and 25% increase for Y3), apply for grants for seed funding or other sponsorship (8% increase for Y2 and 21% increase for Y2), and present their capstone project at conferences or symposia (10% increase in Y2 and 17% increase for Y3). By the second year of the pandemic (Y3), more students reported progress or completion of patent submission (12% increase) and IRB application submission (25% increase) compared with pre-pandemic numbers (Y1). This shows that some project outcomes and productivity were as high, or in some cases, higher during the pandemic (Y2 and Y3) than prior to the pandemic (Y1). This may partly be attributed to some activities being more conducive to the virtual setting (*e.g.*, writing grant applications and meeting with clinical stakeholders), whereas other activities were more challenging (*e.g.*, prototype development and testing). These improvements may also be attributed to students in Y3 having selected and scoped their projects appropriately, with the knowledge that they would be working remotely.

Open-ended survey responses shed light onto the team and design challenges faced by students with the onset of the pandemic and the shift to remote learning. Common themes that emerged included challenges related to communication with teammates and difficulties accessing prototyping and testing resources (Figure 2). While students were generally disappointed around the circumstances, they had an overall positive attitude about working through the challenges to meet common goals. Teams managed these challenges and worked remotely as teams by using a variety of different tools that were reported in the open-ended questions of the survey. Going forward, we intend to continue use of Zoom and MS Teams to facilitate remote communications and engagement with clinical partners.

While individual activities modified (Table 1) or introduced (Table 2) during remote learning were not evaluated comprehensively, we intend to incorporate some of the most effective remote activities into our regular program activities. For example, Shift-and-Share presentations (Table 1) that were modified for Zoom were more efficient to organize and allowed for a wider audience to attend remotely. That is, upwards of 8–14 external guests with many years of experience in healthcare innovation or medical device design participated when presentations were held remotely, compared to 3–5 on average when presentations were in-person. Similarly, the welcome activity to start each class with an engaging activity or interactive poll facilitated community building and camaraderie in both the physical and remote classroom. On the other hand, some activities were not as well-received in the remote setting. For example, virtual tours of clinical and industry settings were appreciated when strict stay-at-home orders were in effect but overall lacked the level of engagement and enthusiasm we expect to see at in-person tours. Moving forward, we intend to use a combination of these remote teaching strategies (Table 1 and Table 2) to deliver course content effectively. We attribute the successful project outcomes and high level of productivity (Table 4) to these innovative approaches, especially when compared with pre-pandemic levels (Table 4, Y1). This suggests that the innovative remote teaching strategies, which include the existing course activities that were modified for remote learning, and the newly added course activities for the remote course environment, provided effective options in the absence of certain hands-on experiences that are considered critical to engineering capstone design courses.

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Appendix A

Surveys administered in capstone class at the end of the fall quarter, and the end of the spring quarter

Two surveys were administered in the capstone class each year. The fall surveys were administered at the end of fall quarter and asked students to respond to questions related to working on teams before and after working in their capstone project teams. The spring surveys were administered at the end of spring quarter and asked students to respond to questions related to their team experience specifically with their project team. The questions are provided below for the fall and spring surveys. Note that for the fall survey, Part 3 was only included in the second and third years of the study (Y2 and Y3), when class was held in a remote environment.

<u>Fall Survey Questions</u>

Part 1: Please think about the times you have worked on group projects or teams in different settings in the past.

1. Prior to your participation in this class, what types of settings have you worked on group projects or teams? (select all that apply)
    a. High School Classes
    b. College (outside of engineering classes)
    c. College (in engineering classes)
    d. Work (paid or volunteer)
    e. N/A
2. Think about your engineering courses. Prior to this capstone class, how many times have you worked on an engineering project as part of a group project or team?
    a. Never
    b. Once
    c. Twice
    d. Three times
    e. Four or more times
3. Based on your *past experience working on group projects or teams* in all the settings you selected in question 1 above (prior to enrolling in this class), please rate your capability of each statement. [*Matrix of options: not at all capable (1), somewhat capable, neither capable nor incapable, somewhat capable, very capable (5)*]
    a. Speak up in team meetings
    b. Effectively contribute in team meetings
    c. Recognize team members' strengths
    d. Resolve conflicts with peers and other project collaborators
    e. Advocate for multiple points of view (different perspectives)
    f. Have your voice heard in team meetings
    g. Collaborate with team members who have different working styles
    h. Clarify language differences across disciplines/backgrounds (e.g., differences in terminology)

Part 2: Please answer the following questions about your experience so far of working this term with your project team.

4. Please rate how satisfied you were in working with your project team this quarter. [*Very dissatisfied (1), dissatisfied, neutral, satisfied, very satisfied (5)*]
    a. Please explain your response.
5. Please rate how satisfied you are with the progress made on your project this quarter. [*Very dissatisfied (1), dissatisfied, neutral, satisfied, very satisfied (5)*]
    b. Please explain your response.

6. Based on your *current experience working in your project team*, please rate your capability of each statement. [*Matrix of options: not at all capable (1), somewhat capable, neither capable nor incapable, somewhat capable, very capable (5)*]
   a. Speak up in team meetings
   b. Effectively contribute in team meetings
   c. Recognize team members' strengths
   d. Resolve conflicts with peers and other project collaborators
   e. Advocate for multiple points of view (different perspectives)
   f. Have your voice heard in team meetings
   g. Collaborate with team members who have different working styles
   h. Clarify language differences across disciplines/backgrounds (e.g., differences in terminology)
7. Based on your current experience working in your project team, please rate your agreement with each statement. [*Matrix of options: strongly disagree (1), disagree, neutral, agree, strongly agree (5)*]
   a. Our project team has been successful working together
   b. Our project team has a climate of collaboration and trust
   c. I felt comfortable giving my team members feedback
   d. I felt comfortable receiving feedback from my team members
   e. Team members on my project had a high level of mutual trust in each other
   f. I had a desire to know my team members on a personal level
   g. Having a successful project was a priority for me
   h. Building effective relationships with my team members was a priority for me
   i. I was comfortable showing the limits or gaps in my knowledge with my team members
   j. Communication with my team members outside of class (e.g., scheduling team meetings) was easy
8. Please briefly describe a "best practice" you found to facilitate successful teamwork with your project team.
9. What other ideas do you have or have you seen that would facilitate successful teamwork for project teams?
10. Please briefly describe one challenge you have encountered in working with your project team and how your team did or did not overcome the problem.
11. How would you describe your main role(s) in your project team? How were these roles determined? Did your role(s) change over time?

Part 3: The following questions are related to your experience with capstone in the virtual classroom environment

12. With the move to remote work due to the COVID-19 pandemic, what strategies and/or tools did your team utilize to work together?
13. How would you rate your experience with using Zoom for [*Matrix of options: N/A, not effective, moderately effective, very effective*]
   a. Course lectures
   b. Break-out sessions
   c. Interacting with other students during class (including breakouts)
   d. Interacting with teaching team during class
   e. Sharing your responses in PollEv
14. How would you rate the effectiveness of MS Teams for [*Matrix of options: N/A, not effective, moderately effective, very effective*]
   a. Office hours
   b. Working on team assignments
   c. Communicating with student team members
   d. Communicating with teaching team
   e. Communicating with project partner(s)
   f. Receiving class announcements

g. Receiving feedback on homework questions and assignments
h. Support and access to instructors outside of class

15. If you are using any of the additional tools listed below, please rate the effectiveness of using them for your team project. [*Matrix of options: N/A, not effective, moderately effective, very effective*]
   a. Slack
   b. Discord
   c. Google Drive
   d. OneNote
   e. Hive
   f. Facebook
   g. Trello
16. Please indicate the extent to which the remote tools and activities helped your team to become more [*Matrix of options: not at all helpful (1), slightly helpful, moderately helpful, helpful, very helpful (5)*]
   a. Efficient (well-organized; minimum wasted effort; reaching milestones in a timely manner; etc.)
   b. Effective (successful in producing desired or intended result; completing milestones; etc.)
17. Please use this space to provide other comments on your experience with the virtual classroom environment.

Part 4: Please answer the following questions about your experience of working this term with your course faculty and clinical partners.

18. Based on your experience this quarter with course faculty, please rate your agreement each statement. [*Matrix of options: strongly disagree (1), disagree, neutral, agree, strongly agree (5)*]
   a. Communication with faculty outside of class (e.g., to get advice or ask questions) was easy
   b. I felt comfortable sharing team project updates with faculty
   c. I felt comfortable receiving feedback from faculty
   d. Building effective relationships with faculty was a priority for me
   e. I was comfortable showing the limits or gaps in my knowledge with faculty
19. Based on your experience this quarter with your clinical partner(s), please rate your agreement each statement. [*Matrix of options: strongly disagree (1), disagree, neutral, agree, strongly agree (5)*]
   a. Communication with clinical partners outside of class (e.g., to get advice or ask questions) was easy
   b. I felt comfortable sharing team project updates with clinical partners
   c. I felt comfortable receiving feedback from clinical partners
   d. Building effective relationships with clinical partners was a priority for me
   e. I was comfortable showing the limits or gaps in my knowledge with clinical partners

Part 5: Please tell us a little about yourself so that we can examine whether there are differences in experience for students according to their demographic and/or educational background:

20. Is English your first language? [*Yes, No*]
21. What is your preferred gender affiliation? [*Male, Female, prefer not to say]*
22. In what type of educational program are you enrolled? [*Undergraduate, graduate, other*]
23. Is there anything else about your experience in this capstone class or working in your project team that you would like to share? Note: If you have a comment that needs a personalized response, please reach out to the instructor.

Spring Survey Questions

Part 1: Please answer the following questions about your experience of working the past two terms with your capstone project team.

1. Please rate how satisfied you were in how your team worked together to complete your project during Q2 and Q3. [*very dissatisfied, dissatisfied, neutral, satisfied, very satisfied*]
    a. Please explain your response.
2. Please compare how satisfied you are in working with your project team during Q2 and Q3 *as compared to Q1*. [*Much more satisfied with Q2/Q3, slightly more satisfied with Q2/Q3, neutral, slightly more satisfied with Q1, much more satisfied with Q1*]
    a. Please explain your response.
3. Please rate how satisfied you are with your current capstone product. [*very dissatisfied, dissatisfied, neutral, satisfied, very satisfied*]
4. Based on your current experience working with your current project team, please rate your capability of each statement. [*Matrix of options: not at all capable (1), somewhat capable, neither capable nor incapable, somewhat capable, very capable (5)*]
    a. Speak up in team meetings
    b. Effectively contribute in team meetings
    c. Recognize team members' strengths
    d. Resolve conflicts with peers and other project collaborators
    e. Advocate for multiple points of view (different perspectives)
    f. Have your voice heard in team meetings
    g. Collaborate with team members who have different working styles
    h. Clarify language differences across disciplines/backgrounds (e.g., differences in terminology)
    i. Incorporate feedback into your project in a productive manner
5. Based on your current experience working with your project team, please rate your agreement each statement. [*Matrix of options: strongly disagree (1), disagree, neutral, agree, strongly agree (5)*]
    a. Our project team has been successful in working together
    b. Our project team has a climate of collaboration and trust
    c. I felt comfortable giving my team members feedback
    d. I felt comfortable receiving feedback from my team members
    e. Team members on my project had a high level of mutual trust in each other
    f. I had a desire to know my team members on a personal level
    g. Having a successful project was a priority for me
    h. Building effective relationships with my team members was a priority for me
    i. I was comfortable showing the limits or gaps in my knowledge with my team members
    j. Communication with my team members outside of class (e.g., scheduling team meetings) was easy
6. Please briefly describe a "best practice" you found to facilitate successful teamwork with your project team. (open-ended response)
7. What other ideas do you have or have you seen that would facilitate successful teamwork for project teams?
8. Please briefly describe one challenge you have encountered in working with your project team and how your team did or did not overcome the problem.
9. How would you describe your main role(s) in your project team? How were these roles determined? Did your role(s) change over time?
10. How likely is it that you and your project team will participate in the following activities related to your capstone project. [*Matrix of options: highly unlikely (1), unlikely, neither likely nor unlikely, likely, highly likely, already in progress, completed (7)*]
    a. Continue to work as a team after the official end of the program year
    b. Complete an IRB application to test your device on human subjects
    c. Manufacture your device, to scale, using the materials you intend to use if your product were to be available for sale
    d. Seek FDA approval for your device
    e. Publish scholarly manuscripts related to your project

f. Present project device at university, local, regional, or national conferences or symposia
g. Complete patent application(s) related to your project
h. Form a commercial entity
i. Apply for grants or seed funding to continue your work on the project
j. Engage in other fundraising activities to continue your work on the project
k. Receive grants, seed funding awards, or other sponsorship to continue your work on the project
l. Obtain press or media coverage of your device at the university, local, regional, or national level
m. Engage in other activities that demonstrate success or productivity on the project
n. If other, please explain here.

11. What is your intention of staying in touch with your project team members? [C*heck all that apply*]
    a. Personally
    b. On this particular project
    c. In school
    d. Professionally
    e. No intention of staying in touch
12. How did the shift to remote work during the pandemic affect your team and/or your project?
13. What strategies and/or tools did your team utilize (or increase use of) during this shift to remote work?

Part 2: Please answer the following questions about your experience of working with course faculty, clinical partners, Team Science, and guest experts.

14. Based on your experience this year with your course faculty, please rate your agreement each statement. [*Matrix of options: strongly disagree (1), disagree, neutral, agree, strongly agree (5)*]
    a. Communication with faculty during class sessions (e.g., to get advice or ask questions) was easy
    b. I felt comfortable sharing team project updates with faculty
    c. I felt comfortable receiving feedback from faculty
    d. Building effective relationships with faculty was a priority for me
    e. I was comfortable showing the limits or gaps in my knowledge with faculty
    f. Communication with faculty outside of class (e.g., to get advice or ask questions) was easy
15. Please describe the role of your faculty and what it was like working with them. How did faculty promote or inhibit effective teamwork and/or productivity?
16. Based on your experience this year with your clinical partner(s), please rate your agreement each statement. [*Matrix of options: strongly disagree (1), disagree, neutral, agree, strongly agree (5)*]
    a. I felt comfortable sharing team project updates with clinical partners
    b. I felt comfortable receiving feedback from clinical partners
    c. Building effective relationships with clinical partners was a priority for me
    d. I was comfortable showing the limits or gaps in my knowledge with clinical partners
    e. Communication with clinical partners outside of class (e.g., to get advice or ask questions) was easy
17. Please describe the role of your clinical partners and what it was like working with them. How did clinical partners promote or inhibit effective teamwork and/or productivity?
18. Please indicate the extent to which the team science sessions/tools helped your team to become more [*Matrix of options: not at all helpful (1), slightly helpful, moderately helpful, helpful, very helpful (5)*]
    a. Efficient (well-organized; minimum wasted effort; reaching milestones in a timely manner; etc.)

b. Effective (successful in producing desired or intended result; completing milestones; etc.)
c. Successful in carrying out your project together

Part 3: Please tell us a little about yourself so that we can examine whether there are differences in experience for students according to their demographic and/or educational background:

19. Is English your first language? [*Yes, No*]
20. What is your preferred gender affiliation? [*Male, Female, prefer not to say]*
21. In what type of educational program are you enrolled? [*Undergraduate, graduate, other*]
22. Is there anything else about your experience in this class or working with your project team, faculty, or clinical partners that you would like to share? Note: If you have a comment that needs a personalized response, please reach out to your course instructors.

Appendix B

Table 1. Student responses to the question, “Prior to your participation in this class, what types of settings have you worked on group projects or teams?”

	High School Classes (%)	College (≠eng) (%)	College (=eng) (%)	Work or Volunteer (%)	N/A (%)
Y1, Fall 2018	78.4	78.4	98.0	70.6	0.0
Y2, Fall 2019	65.5	78.2	90.9	67.3	1.8
Y3, Fall 2020	71.7	80.0	90.0	68.3	0.0

Table 2. Student responses to the question, “Prior to this capstone class, how many times have you worked on an engineering project as part of a group project or team?”

	Never	Once	Twice	Three times	Four or more times
Y1, Fall 2018	0.0	7.5	15.1	13.2	64.2
Y2, Fall 2019	1.9	13.2	9.4	28.3	47.2
Y3, Fall 2020	5.0	6.7	20.0	10.0	58.3

Table 3. Student responses to statements related to project outcomes. Responses are based on students reporting their level of likelihood to complete the listed outcomes on a 3-point Likert-type scale or whether milestone is in progress or completed. For each project outcome listed, the difference (Δ) between Y2 and Y1 (middle column) or Y3 and Y1 (right column) is given for the “In progress or completed” values, where positive differences (indicating improvement in outcomes) are shaded in green and negative differences (indicating poorer outcomes) are shaded in red.

		Y1, pre-pandemic	Y2, onset of pandemic	Y3, during pandemic
IP: Submit a patent application(s) related to your project	Unlikely (%)	15	38	4
	Neutral (%)	15	8	16
	Likely (%)	45	42	44
	In progress or completed (%)	24	13	36
	∆ in progress or completed		**-11**	**12**
IRB: Submit an IRB application to test your device on human subjects	Unlikely (%)	16	54	15
	Neutral (%)	13	8	12
	Likely (%)	66	33	42
	In progress or completed (%)	6	4	31
	∆ in progress or completed		**-2**	**25**
Continue project: Continue to work as a team after the end of the program	Unlikely (%)	19	42	33
	Neutral (%)	38	21	13
	Likely (%)	44	29	29
	In progress or completed (%)	0	8	25
	∆ in progress or completed		**8**	**25**
Seed funding or grants: Apply for grants, seed funding, or other sponsorship	Unlikely (%)	31	54	8
	Neutral (%)	34	8	13
	Likely (%)	34	29	58
	In progress or completed (%)	0	8	21
	∆ in progress or completed		**8**	**21**
Presentations: Present project at conferences or symposia	Unlikely (%)	16	33	12
	Neutral (%)	16	21	20
	Likely (%)	65	33	48
	In progress or completed (%)	3	13	20
	∆ in progress or completed		**10**	**17**
Manufacturing: Manufacture your device to scale using intended materials	Unlikely (%)	22	50	17
	Neutral (%)	28	17	22
	Likely (%)	34	33	52
	In progress or completed (%)	16	0	9
	∆ in progress or completed		**-16**	**-7**
Publish: Publish scholarly manuscript(s) related to your project	Unlikely (%)	23	50	13
	Neutral (%)	20	8	25
	Likely (%)	43	42	54
	In progress or completed (%)	13	0	8
	∆ in progress or completed		**-13**	**-5**
FDA: Seek FDA approval for your device	Unlikely (%)	21	54	26
	Neutral (%)	21	21	17
	Likely (%)	48	25	48
	In progress or completed (%)	9	0	9
	∆ in progress or completed		**-9**	**0**
Press coverage: Obtain press or media coverage of your device	Unlikely (%)	22	52	22
	Neutral (%)	25	24	35
	Likely (%)	50	24	39
	In progress or completed (%)	3	0	4
	∆ in progress or completed		**-3**	**1**
Form company: Form a commercial entity	Unlikely (%)	12	64	13
	Neutral (%)	21	24	38
	Likely (%)	45	12	50
	In progress or completed (%)	21	0	0
	∆ in progress or completed		**-21**	**-21**