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Pivot to Remote Teaching of an Undergraduate Interdisciplinary Project-Based Program: Spring–Fall 2020

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Dr. Timothy Kassis completed his postdoctoral training under Profs. Linda Griffith (BE) and David Trumper (MechE) at MIT. Prior to that, Dr. Kassis obtained a Ph.D. in Bioengineering and an M.S. in Mechanical Engineering from the Georgia Institute of Technology in Atlanta, GA, and a B.Eng. in Electronic and Communications Engineering from the University of Nottingham, UK. Dr. Kassis has lived for extended amounts of time in the Philippines, Canada, UK, Lebanon, Syria, and since 2008, the United States. Dr. Kassis has been a lead instructor at MIT since 2017.

Dr. Kassis is currently the lead instructor for the School of Engineering's New Engineering Education Transformation (NEET) Living Machines (LM) thread and is also the instructor for 20.051, 20.052 and 20.053 which are the three classes entitled 'Living Machines' required by all students participating in the LM thread.

Dr. Kassis' research interests lie at the convergence of engineering, biology, and computation. He is particularly interested in creating engineering tools to answer difficult biological questions. Dr. Kassis has worked on a variety of interdisciplinary research projects from elucidating the role of lymphatics in lipid transport to designing organ-on-chip microfluidic models to developing deep convolutional networks for biomedical image processing.

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Justin Lavallee graduated from the Harvard Graduate School of Design in 2010 with a Master in Architecture. After working as a researcher studying novel applications for industrial robots in custom manufacturing processes, he joined the MIT Department of Architecture in 2011 as an instructor and eventually director of the MIT Architecture Shops. He joined the MIT New Engineering Education Transformation as a lead technical instructor in 2019. Throughout his time at MIT he has focused on developing and teaching courses at the intersection of design, technology, and making, while also participating in a number of research projects focusing on new fabrication techniques.

Dr. Gregory L. Long PhD, Massachusetts Institute of Technology

Gregory L. Long, PhD is currently the Lead Technical Instructor for NEET's Autonomous Machines thread at the Massachusetts Institute of Technology. He has a broad range of engineering design, prototype fabrication, and manufacturing experience, and he has taught mechanical engineering design, robotics, control of mechanical systems, and a variety of mathematical topics for over 20 years before joining the faculty at MIT. He has published scholarly articles on robot mechanics and control, and he has a textbook titled "Fundamentals of Robot Mechanics".

Greg received his bachelors of science degree in chemical engineering from Stanford University, his masters of science and doctorate degrees in mechanical engineering and applied mechanics from the University of Pennsylvania, and his masters of liberal arts degree in mathematics for teaching from Harvard University.

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Work-in-Progress

Pivot to Remote Teaching of an Undergraduate Interdisciplinary Project-Based Program: Spring–Fall 2020

I. Introduction

The COVID-19 pandemic has had a dramatic impact on teaching in higher education, primarily brought about by a pivot to emergency remote teaching about halfway through Spring 2020. This paper provides a detailed account and study of efforts to pivot to remote teaching in the New Engineering Education Transformation (NEET), a project-centric undergraduate engineering education program from Spring–Fall 2020 (two semesters) in Massachusetts Institute of Technology (MIT).

The paper is structured as follows: first, we define remote teaching in the context of this study. Next, we describe the NEET program. We go on to describe the campus shutdown which led to the need for pivoting to remote learning in our program. We then provide an account of our response to the pivot to remote teaching: our immediate response for emergency remote teaching during Spring 2020 as a campus shutdown was announced, and our planned response for remote teaching in Fall 2020. Each account is divided into the five tracks, or threads, of the program: Autonomous Machines, Living Machines, Advanced Materials Machines, Digital Cities, and Renewable Energy Machines; we suggest readers with interest in particular disciplines look into the appropriate sub-section. We then give a summary of feedback on remote teaching during Fall 2020 provided by instructors and students in the program. We end with a discussion of opportunities and challenges that we have identified with remote teaching, and suggestions for undergraduate instructors.

A. Emergency and Planned Remote Teaching

Remote teaching during the COVID-19 pandemic can be clearly divided into *emergency remote teaching* and *planned remote teaching*. Whereas planned remote teaching involves a process of careful design, emergency remote teaching does not involve such a process. This is because the primary objective of emergency remote teaching is to provide access to instruction and instructional supports during a time of crisis, rather than to provide sustainable high-quality instruction. As a result, any pivot to emergency remote teaching mostly involves technological, rather than pedagogical, aspects [1, 2]. In the context of our study, we pivoted to emergency remote teaching halfway through Spring 2020, and shifted to what we will henceforth refer to as *planned remote teaching* in Fall 2020.

B. Description of the New Engineering Education Transformation Program

Present-day industry requires employees and entrepreneurs with skills that are essential for thriving in the 21st century, such as collaboration, communication, creativity, and learning on one's own. Many of these essential skills are not acquired during traditional undergraduate engineering education, centered on lecturers and recitations [3], [4]. The need for students to acquire these skills is also reflected in papers published by the OECD (Organization for Economic Co-Development) [5] and the US NRC (National Research Council) [6]. More particularly in engineering higher education, ABET's *student outcomes* [7] also list some of these essential skills.

For a higher education institution to be able to deliver an education that develops students' essential skills, it must develop strategies for action based on a clearly defined systemic vision [8]. A benchmarking study commissioned by MIT [9] highlighted the need to provide students with further opportunities for practical engineering and for developing the aforementioned essential skills.

The NEET program, launched in 2017, reimagines engineering education at MIT. It is a cross-departmental initiative, focusing on integrative, project-centric learning. The program helps foster the essential skills, knowledge, and qualities required to tackle the complex problems of the 21st century. Students enroll in the program during their sophomore year, and earn a degree in the usual four years in their chosen major, as well as a Certificate in one of program's five interdisciplinary threads: Autonomous Machines, Living Machines, Advanced Materials Machines, Digital Cities, and Renewable Energy Machines. Previous publications have covered past developments in the program [10–12].

The NEET program is based on four student education principles:

1. Prepare students to develop new machines and systems.
2. Prepare students to become makers and discoverers, with fundamentals in engineering applicable to research and practice.
3. Construct pedagogy around how students learn best, to be both effective and engaging.
4. Empower students to think and learn effectively for themselves.

Joining NEET is elective, and does not help toward fulfilling requirements of an engineering degree (major) as prescribed by MIT. However, the requirements for each thread are tailored around the requirements of several majors which are appropriate for that specific thread, and the program does afford a measure of flexibility based on the particular circumstance of each enrolled student. As of beginning of the Fall 2020 semester, 187 sophomores, juniors and seniors were enrolled in the program. The Digital Cities and Renewable Energy Machines threads do not yet have a cohort of senior students, but will in the next academic year (Fall 2021–Spring 2022).

C. Campus Shutdown Spring–Fall 2020

About halfway through the semester, MIT announced that the campus will shut down and that all Spring classes will take place remotely. In addition, grades for classes for the spring semester were changed to pass/fail only.

II. Pivot to Remote Teaching: Spring–Fall 2020

This section covers (a) the program's immediate response to campus shutdown and the pivot to emergency remote teaching from March 30th, 2020 and through the Spring 2020 semester, and (b) its planned response to remote teaching in Fall 2020. We describe the program-wide response, as well as the individual response of each program thread.

A. Emergency Remote Teaching: Spring 2020

i. Program-wide Response

As a project-centric, hands-on program, the immediate pivot to remote teaching was a challenge. With two weeks of Spring break available for preparation, the key challenge was in shifting from on-campus to remote teaching while delivering an adequate learning experience to students and making sure they are able to progress toward completing the program in their thread of choice.

Table 1 details the NEET threads and their respective subjects which were offered during Spring 2020, as well as the key strategies that were employed and whether there was any student collaboration involved.

Table 1. Project-centric subjects taught in the program during Spring 2020.

Program thread	Program year	Subject description	Student collaboration	Key strategies[1]
Autonomous Machines	Sophomore	Building and operating an autonomous robot individually	No	Assembling and programming robot at home
	Junior	Programming an autonomous robot and testing in a virtual environment as a team	Yes	Focus on programming Testing in virtual simulated environment
	Senior	Developing and operating an autonomous robot as a class	Yes	Focus on design and programming Testing in virtual simulated environment
Living Machines	Sophomore	Designing a research study in a small team	Yes	Focus on literature review and simulation
	Junior	Designing and collaborating on a multi-lab research project with fellow students and others	Yes	Focus on simulation and computations
	Senior	Continuing collaboration on a multi-lab research project with fellow students and others	Yes	Focus on simulation and computations
Advanced Materials Machines	Sophomore and Junior	Speaker series with hands-on activities	No	Expanding the range of speakers from regional to global Use materials and equipment that can be mailed to students and worked with at home
Digital Cities	Sophomore	Making and using of environmental sensing device to collect data	No	Building device and collecting data indoors (at home)
	Sophomore	Speaker series	No	Expanding the range of speakers from regional to global
	Sophomore	Design project	Yes	Focus on design and data analysis
Renewable Energy Machines	Sophomore	Speaker series	No	Expanding the range of speakers from regional to global

[1] For all subjects, synchronous learning was carried out on Zoom—a Web-based videotelephony platform.

ii. Thread-specific Response

a. Autonomous Machines

The sophomore class involved the design and planning of a control algorithm for an autonomous robot by individual students. As of the date of campus shutdown, none of the students had a fabrication-ready design for their robots nor a programming-ready control algorithm. Weekly design review meetings with instructors continued remotely, as well as engagement via Slack[1]. One-on-one meetings with the instructor were also offered, but not mandatory. At the end of the semester, all the students had a fabrication-ready robot design and a better idea of how they would control their robots. In retrospect, the additional one-on-one meetings were unnecessary, as the weekly design review meetings with instructors had sufficed. Engagement via Slack was modest, but understandably low as we directly answered the student questions in the weekly design review meetings.

The junior class involved small teams of students working on algorithm development for an autonomous robot which was more advanced than the one sophomore students had worked with. Following the pivot to remote learning, students continued to work on algorithm development via computer simulations. Lecture recordings were provided to students living in time zones different from where MIT campus resides. Students submitted weekly team assignments and presentations, and met weekly to collaborate. Additionally, students were given 'office hours' for consulting with the teaching assistants. Whereas the coding assignments were virtually unaffected, testing transitioned to photorealistic simulation, as students no longer had access to the physical cars.

For the senior class, students were working on their class-wide project, which was to design and develop an advanced autonomous robot. Following the campus shutdown, the nature of the project changed from hardware (robot) to software simulation of the hardware. They continued to meet weekly to collaborate on product development. We believe that working with the simulation could have had an almost equal outcome to working with a real robot, if students had more time to work with it. It became difficult to track progress over the course of a week when the students are remote, as there is no interaction in the lab that would happen naturally. This resulted in issues being raised, or revealed, at a slower pace than when teaching on-campus.

b. Living Machines

The sophomore class involved lab-based research and reporting in small teams. Following the campus shutdown, the fabrication aspect of the research was removed, and the focus of the work

[1] A commercial Web-based software application for collaboration via instant messaging: https://slack.com/

shifted to virtual, specifically simulation, computation, and literature review. While simulation was already a part of the class, it now became more prominent, and students ended up using the more advanced features of COMSOL[2] to take the place of in-lab experiments. Students were provided with support from within the host department for using COMSOL. However, teams' proposals were not altered from before the campus shutdown. One deliverable was removed from the class to adjust for the sudden shift to remote learning and relocation which students had to go through. Feedback was provided to student teams in-class every one to two weeks, and students were free to request meetings with instructors and with the teaching assistant. Additionally, the symposium which was planned for the end of the semester was cancelled. The final presentations and all the class meetings remained the same, except they took place via Zoom. Students followed up with all the deliverables and produced impressive results for just five weeks of work.

Juniors and seniors continued working on their own multi-lab research projects with other researchers. Research projects containing an in-lab element were converted to purely computational.

c. Advanced Materials Machines

Following campus shutdown, students in this thread were given the option to drop the semester without it affecting their enrollment in the program. The spring class, which was open to all years in the program, involved a speaker series and hands-on activities. Students were given a list of activities to choose from, and had an activity kit mailed to them in accordance with the activity they had chosen. Each student had to carry out the activity, and document their process and outcome. Attendance in these speaker meetings was not mandatory. During the final meeting at the end of the semester, instead of having a speaker, each student presented their activity and shared their thoughts. This provided students with some face-to-face interaction, albeit a virtual one. However, despite efforts to create opportunities for student engagement, there was an understandable lack of interaction while they were working individually at home.

[2] A commercial software application for fluid dynamic simulation.

d. Digital Cities

All three classes taking place during spring 2020 were open to all students in this thread—sophomores and juniors. One class involved individual students building a sensor for monitoring ambient air quality. When campus shutdown was announced, this work was sped up to make sure students had completed building their sensor before they had to leave campus. The sensors were shipped to students, and students connected them to the Cloud. The focus on data collection was changed from outdoors to indoors, i.e., the students' residence.

Another class was a speaker series, and it continued as before, except that it took place on Zoom rather than on-campus. The instructor did individual check-ins with students in case they required assistance with anything concerning their studies. When the instructor 'passed the mic' to students during a virtual event, they asked questions and engaged in the conversation with the instructors and guests.

The third class was a half-term class. The instructor switched to full remote learning a week before campus shutdown took effect. The instructor made lecture recordings available for students, had virtual office hours for students, and communicated with students via Slack.

Student teams continued working on their projects concerning the application of data science to urban challenges. The instructor connected the class to the public health crisis brought on by the COVID-19 pandemic, for example, data visualization of COVID-19 cases, the controversy on contact tracing using digital apps, the role of urban mobility in the spread of virus, and equity issues involving viral exposure and access to health resources during the pandemic. Students presented their projects in the middle of the semester. Student were given the option to submit mockups instead of functional prototypes, and one-third of the students chose this option. Since the class is about data science and students fully work on their own laptop, not relying on physical labs or infrastructure, there were probably less difficulties in transitioning into a virtual environment. Students met during class time in Zoom breakout rooms and planned their work outside of class. The instructor made frequent use of breakout rooms and the chat function to help facilitate group discussion.

One class session was cancelled to allow student to move out of campus and into their new residences. The final exam was also cancelled, in line with MIT's policy. A skill-building workshop also had to be canceled due to time constraints.

e. Renewable Energy Machines

The Spring 2020 class was a speaker series, and open to all years in the program. Every week, a guest speaker with expertise in the field of energy would join the class on Zoom. Attendance was not mandatory, and there was lower attendance than when this class was held on campus. Due to the remote format, the instructor was able to secure speakers from further afield than usual.

B. Planned Remote Teaching: Fall 2020

i. Program-wide Response

The key challenge for the Fall semester was similar to that of Spring 2020: to deliver a sufficient learning experience for project-based and hands-on classes. Even though we distinguish in this paper between emergency remote teaching during Spring 2020 and planned remote teaching during Fall 2020, in reality Fall 2020 still had elements of emergency teaching; specifically, due to the uncertainty of the on-campus situation and the additional instructional workload required by emergency remote teaching during Spring 2020, the program instructors did not have sufficient time to engage in careful design and planning of remote teaching considered as necessary for effective online learning [1]. An additional challenge during this semester was that it became more difficult for students and for program administration to postpone classes to a future semester, as this would have delayed the timeline for completing the program.

Through sheer serendipity, revised requirements for each of the five threads were released in April 2020 soon after the mid-Spring pivot. We had been working on those since early Fall 2019, well before the onset of the pandemic. However, since the revised requirements incorporated greater flexibility, more options and reduced workload for the students, it allowed both students and the program to have greater latitude as they dealt with the uncertainty caused by the pandemic while planning for courses to take in Fall 2020 and beyond. Another serendipitous act was the drafting of new class syllabi based on the revised programmatic requirements, which were more comprehensive than the previous syllabi.

Table 2 details the program threads and their respective subjects offered during Spring 2020, as well as the key strategies that were employed and whether there was any student collaboration involved.

Table 2. Project-centric and other subjects taught in the program during Fall 2020.

Program thread	Program year	Subject description	Student collaboration	Key strategies[1]
Autonomous Machines	Sophomore	Building and operating an autonomous robot individually	No	Assembling and programming robot at home
	Senior	Designing an autonomous robot as a class	Yes	Focus on design and programming Testing in virtual simulated environment
Living Machines	Sophomore	Designing a research study in a small team	Yes	Subject moved to the following semester (Spring 2021)
	Junior	Designing and collaborating on a multi-lab research project with fellow students and others	Yes	Exclusive focus on simulation and on the mathematical aspects of research
	Senior	Continuing collaboration on a multi-lab research project with fellow students and others	Yes	Exclusive focus on simulation and on the mathematical aspects of research
Advanced Materials Machines	Sophomore, Junior, and Senior	Speaker series with hands-on activities	No	Expanding the range of speakers from regional to global Option granted to students to move subject to the following semester (Spring 2021)
Advanced Materials Machines + Renewable Energy Machines	Sophomore	Design-based projects in small teams	Yes	Focus on materials that can be mailed to and worked with at home
Digital Cities	Sophomore and Junior	Speaker series and independent study	No	Expanding the range of speakers from regional to global
Renewable Energy Machines	Sophomore and Junior	Speaker series	No	Expanding the range of speakers from regional to global

[1] For all subjects, synchronous learning was carried out on Zoom—a Web-based videotelephony platform.

ii. Thread-specific Response

a. Autonomous Machines

For the sophomore class, each student was provided a kit with a small suite of sensors, a custom-made mini robot, several hand tools, and two challenges for the robot to navigate autonomously. Using Zoom, we employed one main room for the lectures with nine breakout rooms (with three to five students in each room), and one teaching assistant assigned to three clusters of lab rooms. Both the instructor and teaching assistants were allowed to move freely between the main room and all nine lab rooms, however, the student could only move between the main room and their assigned lab room.

The senior class was devoted toward teaching the students a) how to acquire sensor data, b) how to implement several digital filtering algorithms, c) how to structure their computer code via state machines to manage control flow, and d) how to use the sensor data for autonomous navigation. During summer planning, the instructional team discussed how to mitigate the mechanical assembly, electronics trouble-shooting, and computer code debugging issues that normally occur with hands-on robotics instruction. To mitigate the assembly and electronics issues, we opted to send each student a pre-assembled robot; however, this plan was ultimately delayed two-weeks into the fall semester because it took longer than expected to receive several components from vendors as well as to assemble all the robots. Through the experience gained this semester, we learned how to run a laboratory-style robotics-based class remotely with manageable electronics trouble-shooting and computer code debugging.

b. Living Machines

Sophomore students in this thread are required to take a hands-on, lab-based introductory class. After considering multiple virtual lab options, we decided not to offer this class in the Fall, but instead allow the students to take it later. Juniors and Seniors in this thread had also planned to pursue various research activities on campus through a variety of MIT-provided mechanisms that would fulfill some of their research requirements for this thread. We were able to work with the majority of the students to help them transition to a computational-based project that did not rely on lab facilities.

Students proved to be very resilient and quickly adapted to the new format in teaching; however, they were disappointed by the fact that they could not pursue any of the physical lab activities that would normally accompany their research experiences in the biotech and medical device fields. We found that while students still fulfilled their academic requirements, their participation in non-academic activities such as optional technical workshops, socials and other events dropped significantly compared to on-campus events in the past.

We found that team-based projects are more difficult as students typically find it easier to work together in the same room. Another issue which came up is that it became more difficult to reach students. Finally, we found that virtual social events became more difficult to organize than on-campus ones, as most of the events we have held in the past revolved around sharing a meal, which we found difficult to do over video calls.

c. Advanced Materials Machines

Our primary goal for remote coursework was to make sure there was a hands-on component, since we are a project-based curriculum. For the course with the speaker series and hands-on activities, we looked at different options and decided to send the students a 3D printer kit, and built the course around assembly of the kit. For the sophomore project class, it was necessary to make sure there was physical prototyping in as many of the design projects as possible, while keeping material costs reasonable. In each case, the goal was to focus the assignments on core learning objectives, taking care to make sure the minimum requirements were not too ambitious, since the efficiency of providing remote support for hands-on learning is much lower than for in-person learning. We also created some extra assignments to challenge the category of students who had sufficient experience to easily meet the minimum requirements and a desire to push further.

A frequent comment made by students in this class has been that the course was the only one the student had taken with a hands-on component. Course enrollment was as high as we would typically expect, and attendance and participation stayed throughout the semester. The biggest challenges we faced in this thread were not pedagogical, but more related to procurement and shipping logistics.

d. Digital Cities

This thread had planned to adapt remote teaching for Fall 2020 through a combination of three approaches. The first approach was getting to know where the students are and their course plans for the fall semester. Students live in different cities around the world. The time-zone differences plus conflicting class schedules created a significant challenge for students to meet together at the same time virtually; mitigating this required a flexible class schedule. The instructor adopted a polling approach to schedule events based on the best date and time that may work for most students and allowed a hybrid learning between live participation and asynchronous learning. The second approach was to increase virtual office hours and remind students of the instructor's availability and willingness to communicate. Though the instructors fully adjusted the learning activity and material for the remote environment, it was still challenging to initiate informal communication with students and to virtually mimic a casual chat in the hallway or at the 'watercooler'. Since students are expected to conduct independent study, the instructor ensured one-on-one checkup discussion to get updates and keep track of each student's progress. The third approach was to in parallel provide more guidance and space for students to succeed in remote learning without screen fatigue, overloaded homework, and burnout caused by unnecessary virtual activities.

e. Renewable Energy Machines

The seminar class, which was open to all years in the thread, consisted of a guest lecture series where experts from a variety of academic fields and also from industry led a discussion with students. Attendance was not mandatory. When on campus, we would usually meet together over dinner and make it a social meet-up in addition to an academic class. When we moved this class remotely, we unfortunately had to eliminate the dinner aspect. We tried to keep the lectures informal and have many opportunities for students to participate in discussion actively rather than being passive listeners. One benefit of holding the class remotely is that we have been able to invite guest speakers from remote locations, such as from Silicon Valley in California or Mongolia. Participation in the seminar was on par with what we had experienced on campus.

For the sophomore project class, which is joint with the Advanced Materials Machines thread, the class was focused on learning and practicing the design process, through a series of projects that focus on building specific skills. In person, this involves the use of a machine shop, where students can use tools such as laser cutters, 3D printers, and traditional machine tools like saws and drills. These implements were unavailable given the remote teaching situation, so we pivoted towards tools that can be used in a dorm room with simple kits that included basic tools. This class included three projects: sketch models, computer-assisted design (CAD), and designing a user experience. Students were also tasked with giving other design criticism for the first project. As for the second project, despite the lack of access to shop machines, many students were able to create impressive objects from this project. Some students struggled, perhaps due to less refined craft skills. However, this difference in performance is often also observed when the class is taught in person. For the third project, students seemed adept at picking up the skills to make digital prototypes.

III. Feedback from Instructors and Students on Fall 2020

During Fall 2020, we carried out an evaluation of the program which included, among other instruments, two surveys: one for program instructors (Survey of Instructors), $N = 6$, and another for students in the program (Survey of Students), $N = 26$, which represented ~15% of the total number of students enrolled in the program. Each survey included both open-ended and closed-ended items. The closed-ended items required respondents to give a score from 1 to 5, indicating their level of agreement with a given statement. We include herein the findings pertaining to the remote teaching experience of instructors, followed by the remote learning experience of students.

A. Feedback from Instructors

All respondents to the Survey of Instructors ($N = 6$) agreed to some extent (strongly or otherwise) with the following statements 'I am receiving all the support I require for remote teaching of my program-specific subject/s' and 'I am receiving all the support I require for remote teaching of my program-specific subject/s'.

Respondents to the Survey of Instructors were asked to note things they liked and things they did not like about remote teaching. Their responses can be summarized as follows:

- They liked the greater flexibility in scheduling afforded to themselves, for students and for guest speakers.
- They did not like the lack of access to on-campus facilities related to making activities, and the limited interaction afforded by the virtual platforms used.

B. Feedback from Students

We note at the outset that 17 out of the 26 respondents to the Survey of Students were sophomores in Fall 2020, and in their first year of the Program; therefore, their entire experience in the Program thus far has been virtual, unlike junior and senior Scholars, for whom the Program has previously included on-campus experiences.

18 of 26 respondents to the Survey of Students agreed to some extent (strongly or otherwise) with the statement 'I receive the support I require for remote learning of program-specific subjects'. Two respondents disagreed somewhat with this statement. No respondent

strongly disagreed with this statement. In a subsequent open-ended item, respondents were asked to explain their choice for the previous, close-ended item. On the whole, responses (N = 13) indicated that Thread Instructors were supportive and attentive to Scholars throughout the semester, and allowed scheduling flexibility were Scholars required it.

11 of 25 respondents to the Survey of Students agreed to some extent (strongly or otherwise) with the statement ‘I enjoy remote learning of program-specific subjects’. Four respondents disagreed to some extent (strongly or otherwise) with this statement, while 10 respondents were indifferent to this statement.

17 of 25 respondents to the Survey of Students disagreed to some extent (strongly or otherwise) with the statement ‘Remote learning of program-specific subjects is as effective as on-campus learning would be’. Only one respondent agreed with this statement. In a subsequent open-ended item, respondents were asked to explain their choice for the previous, close-ended item. On the whole, responses indicated the following:

- Remote learning cannot fully replace the on-campus experience, especially when it comes to facilities for research (labs) and making activities (such as the machine shops), and when it comes to collaboration between Scholars
- Thread Instructors and the threads in general are doing their best given the situation
- Some responses indicated that they had no room for comparison between remote and on-campus learning, and therefore did not provide any information

Table 3 summarizes the range of median ratings given by respondents to six program-specific subject evaluations in Fall 2020. Potential ratings ranged from 1 (highly negative)–5 (highly positive). Response rate ranged from 11–38% of the total number of students enrolled in that subject. Not all aspects were relevant for all subjects. There was no evaluation for two classes: Autonomous Machines senior students, and Living Machines sophomore students.

Table 3. Range of median ratings for remote learning aspects of Fall 2020 subjects.

Remote learning aspect	Range of median ratings (out of 4)
Working on problem sets with others	4.0
Recitations	4.0
Labs	3.8–4.0
Collaborative work	3.5–4.0
Synchronous activities	3.0–4.0
Written assignments	3.0–4.0
Office hours	3.0–4.0
Asynchronous activities	2.8–4.0
Presentations	2.7–4.0
Discussion forums	2.4–3.5

IV. Discussion

This section is divided into two sub-sections: first, we discuss the opportunities and challenges of remote teaching, as evidenced by our experience. Next, we make suggestions concerning remote teaching for undergraduate engineering instructors.

A. Opportunities and Challenges of Remote Teaching

We identified four key challenges for remote teaching in our program: (1) the inability to replace some hands-on activities with remote teaching, in particular those activities requiring a lab or machinery; (2) difficulties with creating complex, meaningful interactions between students and instructors, and between students, within the virtual space; (3) adjusting to students in different time zones and circumstances; and (4) balancing program requirements with equity and the impact of the pandemic on students' learning conditions. The availability of fault-free and fast internet access and connections, of residential conditions conducive to learning and of supportive family-related circumstances was critical.

We also identified opportunities brought on by remote teaching: (1) not being tied to a specific location can allow for more flexibility in planning and execution of instruction, as we no longer need to have everyone in the same physical place every time we meet; (2) less time for going from lesson to lesson allows for more efficient and flexible scheduling, which could be more suitable for a larger number of students; and (3) pivoting to remote teaching is an opportunity for instructors to learn how to apply new pedagogical methods and how to use new instructional tools, and more generally, to review their approach to instruction to continue to make it engaging for students.

B. Suggestions for Undergraduate Engineering Instructors

Based on our experience with the pivot to remote teaching over Spring–Fall 2020, we can make some suggestions and observations for undergraduate engineering instructors engaged in remote teaching. We divide our suggestions into those related to curriculum and those related to instruction.

i. Suggestions related to curriculum:

- Shift the focus to learning activities that students can carry out at home or virtually, and without being in the same location as other students.
    - Examples: conducting a literature review, design a product/machine using CAD or other software, programming of remote/virtual machines, conducting simulations in virtual environments, and carrying out hands-on activities at home with mailed-in kits.
- When viable, allow students more flexibility with their trajectory through the course or program they are enrolled in, including postponement to a later semester.
- A comprehensive syllabus is helpful in helping students with understanding class requirements and instructor expectations, and is even more helpful in a situation where students are isolated and are less able to ascertain how they are doing at any given time during the semester.
- Pay attention to extra costs incurred by changes to the curriculum when pivoting to remote teaching, such for mailing equipment to students and using Cloud services.
- Some learning activities cannot be made virtual. Plan for when students get back on campus, and how they will be able to compensate for whatever learning they may have missed out on.

ii. Suggestions related to instruction:

- Remote teaching makes it more difficult to identify and mitigate for students' difficulties with understanding the material or practicing the skills required for a class. As they are isolated, students cannot rely as much on their instructors and peers as they can when they were on campus. Therefore, pay extra attention to the specific situation of each student in your class and try to ascertain what knowledge and skills they have come in with.

- To encourage social interaction among students, design activities where they can interact with each other within and outside of lessons, such as breakout rooms and team assignments.
- When appropriate, take advantage of the much larger potential pool of guest speakers.
- Facilitate group discussion synchronous learning by using the breakout rooms and chat, rather than simply posing questions to the entire class.
- Different platforms facilitate different kinds of interactions. Use a variety of platforms for student communication and collaboration, as well as for communication with you, the instructor. For us, Zoom worked well for synchronous learning, Slack for instant messaging and collaboration outside of lessons, and Canvas for a learning management system[3].
- Not all students are proactive. Approach students and ask them about their ideas for projects and for research, instead of waiting for them to come to you.

C. Conclusion

The pivot to emergency remote teaching has been taking place in numerous institutions around the world [2]. NEET's experience since the campus shutdown at the end of March 2020 has been one of mostly emergency remote teaching with some planned remote teaching. We have learned that flexibility is key to ameliorating this challenging situation, on the part of program administration, instructors, and students. Fortunately, most program requirements were covered adequately, with some resourcefulness and creative thinking on the part of the instructors. However, it is equally as important to keep in mind that certain aspects of program curriculum, in our case the hands-on aspect, may not have an adequate remote substitute. In such cases, flexibility is required in rearranging the program curriculum. We believe the remote teaching proficiencies we have honed and developed from Spring–Fall 2020 will also serve us for post-COVID teaching, as we intend to maintain some of those components even when we are fully back on campus.

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