TEACHING PROCESS AND PLANT DESIGN IN THE YEAR OF COVID-19

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INTRODUCTION

Overview

In March 2020 the COVID-19 pandemic imposed a lockdown in Israel. As with most of the academic world, all teaching at the Technion (the Israel Institute of Technology) had to be conducted online. This paper describes the online flipped class teaching approach piloted for an elective course on plant design to a small cohort of 15 students. Because the class size was so small, no meaningful quantitative analysis was possible on data from the first lockdown semester. However, recommendations for online teaching that were distilled from the experience were implemented in the capstone process design course (a prerequisite for the plant design course) taught in the subsequent second lockdown semester in the winter of 2020/21 to a class of 53 students. This paper discusses the impact of the online teaching approach on the students' perceived learning as well as on the learning outcomes. The author provides insights into how active learning changed during the pandemic and suggestions for effectively supporting learning in virtual active learning classrooms, particularly in the social aspects of learning. This reflective practice paper closes with general recommendations and takeaways for both face-to-face (F2F) and online flipped teaching to support active learning.

F2F Active Learning

The teaching pedagogy to be discussed in this paper is flipping-facilitated active learning. Bloom[1] compares alternative instruction modes to conventional lecture-based teaching that often leads to a wide distribution of summative (exam) scores, resulting in a significant portion of the class not achieving mastery-level. In contrast, "mastery learning," which fosters active learning by students, usually leads to a less dispersed distribution of exam grades with a higher average, and in which a higher proportion of the class achieves the required mastery. Among the factors listed by Bloom[1] as having significant positive effects on achieving learning mastery are positive reinforcement and praise from the instructors, student classroom participation, and time on task, each of which improves results by approximately one standard deviation. Two desirable key features follow from the spirit of Bloom's ideas:

- One should support the acquisition of knowledge and skills mastery by creating opportunities for active learning rather than less-effective passive learning.
- Learners should be encouraged to experiment, even if they make mistakes or fail.[2] Learning is all about trying, failing, understanding why one fails, then trying again, and repeating the process as necessary.

Classification of the degree to which students learn actively is summarized in the so-called ICAP principles,[3] which categorize the degree to which the learning activities are "passive," "active," "constructive," or "interactive." Sufficient staff-student contact time needs to be made available for active learning and experimentation, time that in a conventional setting is taken up by lecturing. This reallocation is accomplished by implementing "flipped classroom" instruction, where home and class activities are "flipped;" that is:

- What used to be class activities (lectures given by teachers) is moved to home activities to be completed by students as preparation. These are a combination of pre-recorded lectures, readings, online quizzes, and other individual assignments.

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- What used to be homework (exercises, computational assignments, and project work) is moved to class activities, to be performed individually or in groups by students, with lecturers and teaching assistants present in guide and mentor roles.

The main justification to move to flipped format is the desire to increase the proportion of the student-staff contact time during which students are actively learning rather than just listening to lectures.[4-5] There are many existing studies that provide quantitative evidence that active learning increases the degree of students' engagement and, consequently, improves course outcomes.[6-8]

Online Learning in the COVID-19 Pandemic

Because of the COVID-19 lockdown limitations, all class meetings had to be conducted online using Zoom® (https://explore.zoom.us/about) with no F2F contact between the course staff and the enrolled students, nor between the students themselves. As one would expect, and especially in the context of the COVID-19 pandemic, there has been a plethora of articles published on reports of active learning to address teaching chemical engineering in general[9-14] and process design in particular.[15]

The lockdown limitations imposed several challenges, starting with the social costs inherent in online rather than F2F contact, which especially tests the effectiveness of team effort in the course's extended design project. On top of that, the effect of attrition stemming from extended lockdowns impacted the students' stamina.[16-18] In this context, consider the five tips for improving the effectiveness of remote instruction reported by Gewin,[19] namely: (1) avoiding transforming all lectures to video, leaving key course concepts to be covered interactively with students; (2) avoiding reliance on synchronous delivery of content, since its quality is often poor and communication links can be unreliable; (3) inviting student engagement and feedback; (4) checking often on students to make sure they are on board; and (5) identifying and supporting struggling students.

THE PLANT DESIGN COURSE AS TAUGHT IN 2019/2020

Plant Design is an elective course that is offered at the Technion in the spring to eighth (and last) semester Chemical Engineering undergraduates. It follows a sequence of compulsory process design courses, starting with the *Process Simulations Laboratory*, taught in the spring to sixth semester students, followed by *Integrated Process Design*, taught in winter to seventh semester students. For a complete description of the evolution of the process design sequence at the Technion, see Lewin and Barzilai.[8] Up until 2019/2020, *Plant Design* was offered in the traditional format: the theoretical content was delivered by F2F lecturing, with the remaining class time reserved for exercises.

Learning Objectives and Desired Outcomes

General Objectives. Students enrolled in this course participate in the development of a process package, as an "employee" of an imaginary company, assigned to a section group. The course simulates the main tasks of such an engineer, who is expected to exhibit management and leadership skills. The principal course deliverable is a complete process package — a project report that includes technical information such as process flow diagrams (PFDs), piping and instrumentation diagrams (P&IDs), and unit mechanical design details and their specification sheets — developed by teams consisting of the student-engineers of each company. In 2019/2020, two engineering "companies," *Green Engineering* and *Blue Technologies*, competed for a bid to develop a complete process package for a 90,000 ton/year methyl chloride plant. Each company was assigned one of the more successful process designs prepared in the previous *Integrated Process Design* course and was organized into 2-3 engineering teams, each responsible for the design of one of the process sections.

Learning Outcomes. The design capabilities that each student is required to demonstrate by the end of the course are (listed in the order that the topics are taught): (a) plant-wide control system configuration; (b) plant-wide layout; (c) mechanical design of pressure vessels, heat exchangers, reboiler circuits, distillation columns, furnaces, and compressors; (d) pipe sizing for single- and two-phase streams; and (e) pump and control valve sizing. Detailed learning objectives are defined for each of these subjects; for example, for the case of heat exchangers, the learning objective is, "Perform the mechanical design of shell-and-tube heat exchangers, including the selection of appropriate configuration (number of shells, and the number of tube and shell passes per shell), materials of construction (for the shell and the tubes), shell diameter and tubesheet selection, such that the required heat duty is obtained with minimum required heat-transfer area, while sustaining reasonable pressure drops in both tube- and shell-sides." Several literature sources are employed to support the course, spanning from textbooks on process design,[20-21] to more specific resources, such as those covering the design of heat transfer equipment,[22-23] and distillation columns.[24-25]

Delivery Deadlines. The members of each company have a collective responsibility to deliver a complete process package on time. The numerous tasks to be accomplished are on a tight schedule consisting of 11 deliverables. The first nine of these involve specific focus on aspects of the design work (e.g. team organization, design of heat exchangers, distillation columns, and reactors, rigorous economic analysis, and preparation of

P&IDs), with the last two deliverables being the submission of the final process package and its oral presentation. The busy delivery deadline schedule was unchanged during the online version of the course in Spring 2020, out of necessity – the student teams needed to produce their process packages on time at the end of the semester.

Grading. The course grading is distributed according to Table 1. To pass the course, a student must obtain a passing grade (55% and above) in the proficiency exam.

TABLE 1
Typical Distribution of Grading in Plant Design

Component	Percentage of Total Grade
Proficiency exam	30%
Individual grade	10%
Group progress (Deliveries 1-9)	10%
Final project reporting (Deliveries 10-11)	50%
Total grade	100%

Course Schedule

The course meetings consist of morning and afternoon sessions of three hours each on the same day. As shown in Table 2, the course is divided into two parts; the first part covers the theoretical material to support mechanical design of equipment, and the second part is devoted to group meetings intended to assist the design teams towards successful final deliveries, where the instructor plays a mentoring role. Before 2018/2019, this material was covered by F2F lecturing, with both morning and afternoon sessions allocated to covering the material. Design meetings were mostly allocated time in the second half of the semester. In 2019/2020, the course was taught in flipped mode for the first time, where the same structure shown in Table 2 has been retained, but with each week of activity consisting of three components:

- For homework and in advance of a week's activities, students are expected to complete online lessons covering all of the course materials, consisting of segments of video clips and associated quiz questions.
- A workshop in which the week's materials are applied in design-type calculations.

TABLE 2
Course Organization for Plant Design

Part 1: Design Background			
Week	**Homework (Online)**	**Class Meeting (Morning)**	**Group Meeting (Afternoon)**
1	L01: Plantwide Layout L02: Pressure Vessel Design	Introduction	Designing Pressure Vessels Workshop (WS)
2	L03: Heat Exchanger Design	Designing Tube & Shell Heat Exchangers WS	Automating Tube & Shell Heat Exchanger Design WS
3	L04: Reboiler Circuit Design	Designing Thermosyphon Circuits WS	Group Meetings – Organization
4	L05: Distillation Column Design	Designing Distillation Columns WS	Group Meetings – Progress on Heat Exchanger Design
5	L06: Furnace Design	Designing Furnaces WS	Group Meetings – Progress and Questions
6	L07: Pipe Sizing L08: Pump Sizing	Pipeline and Pump Sizing WS	Group Meetings – Progress and Questions
7	L09: Valve Sizing L10: Compressor Design	Valve Sizing and Compressor Design WS	Group Meetings – Progress and Questions
8	Proficiency Exam		
Part 2: Group Meetings			
Week	**Group Meeting (Morning)**	**Group Meeting (Afternoon)**	
9	Progress Report on Reactor Design	Progress Report on Column Designs	
10	Progress Report on P&ID Preparation	Progress Report on Economic Assessment	
11	Final Presentation Practice	Final Presentation Practice	
12	Free	Final Presentations	

- A group meeting in which aspects of the design project are discussed and associated calculations performed. The implementation of the flipped classroom, integrating self-paced on-line lessons, interactive class meetings, active tutorials, and group design-related activities mentored by the course staff, represents an updated instance of personal tutoring proposed by Bloom.[1]

Thus, the conventional lectures have been replaced by students self-studying the lecture materials, thus freeing the available student-staff contact time for the features indicated by Bloom as contributing to learning mastery. This first part ends with a proficiency exam to test each student's understanding and capability on the application of the acquired knowledge. The exam consists mostly of multiple-choice questions with a few questions involving computations.

The second part of the course provides time to support project work and includes two meetings a week with each group, each meeting dedicated to discussing specific aspects of the project. The teams are expected to come to each meeting ready to make presentations on relevant subjects; this gives them an opportunity to ask questions and discuss specific problems, thus triggering brainstorming and additional class discussion. Note that the meetings held one week before the end of the course are allocated to practice for the final presentation. The last class meeting, held on the last afternoon of the course schedule, is reserved for the final project presentations. Scheduling the presentations in the afternoon makes it easier for invited guests from industry to participate and to evaluate the students' presentations without disturbing their workday. In 2019/2020, given the usage of Zoom for all meetings, running the final presentations on Zoom made it possible to invite guests from all over the world, with the final presentations scheduled for the afternoon to enable evaluators from 11 time zones, spanning from Texas to China, to attend at reasonable local times.

Resources Available in the 1st Lockdown Semester

The flipped version of the course consists of 10 Moodle™ Lessons, each covering one of the design subjects taught in the first part of the course. Each Moodle Lesson is organized as a series of segments comprising one or more quiz questions accompanied by an embedded video clip. Depending on the materials covered, the lessons consist of between five and twelve segments, each covering an aspect of the subject matter. For example, the lesson on heat exchanger design has 12 segments and contains 21 questions to test the students' comprehension, organized as in Table 3. Each lesson involves mostly basic- and intermediate-level, retention-type multiple-choice questions, with a few higher-level questions to make things more interesting for the more accomplished students. Note that each possible answer receives a response, whether correct or not. In the case of an incorrect answer, the response will at least provide a hint to the student that will explain why it is incorrect. The course policy is to allow the student up to four attempts, so in the case of multiple-choice questions, every student can eventually get the correct answer by perseverance. This is the intended result, so long as the student also reads explanations for any errors made along the way.

Lockdown teaching depends on the availability of a learning management system and its associated components. The tool hierarchy is:

- Learning Management System (LMS) – A support system that combines information storage, task management, engagement monitoring, testing, and grading. Examples of widely used systems are Moodle, Canvas®, and Open EdX ®. At the Technion we have relied on the open-source Moodle LMS for more than 15 years.
- Video Streaming Service (VSS) – A system that enables recording, uploading, management and streaming of videos, with the former being key to effective dissemination. Examples of such systems would be Panopto® and Zoom, with the latter being our preferred solution.
- Video recorder and editor – Such applications enable the recording of lectures and their editing. Examples of such systems would be Camtasia® and Filmora X™, with the former being the author's preferred solution. Of course, lecture segments can also be recorded and edited in a professional studio by the studio's technical staff. This option potentially leads to superior results but is difficult to sustain in a campus-wide setting as it would limit the number of courses that can be simultaneously upgraded to flipped format by the number of studios available. In any case, the lecturers are still required to perform all the preparation work on their own, which constitutes most of the effective load.
- Online video communication – Such systems support video and audio conferencing, chat, polling, and webinars. Examples of such systems are Zoom and Teams, with the Technion, like most universities in the world, opting for Zoom.

To monitor students' engagement with the learning materials and in class meetings, most of the above components feature logging and tracking. For example:

- Moodle lesson engagement time: For each student, this feature tracks time on task, as well as lesson repeats and quiz scores.
- Zoom meeting attendance: Each attending student is logged.
- Video engagement time: One of the features of the

TABLE 3
The Segments of Moodle Lesson 3 (Mechanical Design of Heat Exchangers)

Segment	Embedded Video (note viewing times)	Quiz Questions/Assignments
L03.01	**Introduction:** Learning objectives and list of topics covered in the lesson (2 min).	Cluster of two basic-level multiple-choice (MC) questions
L03.02	**Shell-and-Tube Heat Exchangers:** Introduction to TEMA configurations and tube/shell stream assignment rules (13 min).	Cluster of three basic-level MC questions.
L03.03	**Fin-fan Heat Exchangers:** Brief introduction to the fin-fan heat exchanger including simple design rules (3.5 min).	MC basic-level question to test retention of materials.
L03.04	**Introduction to Furnaces:** Brief introduction to fired furnaces (4.5 min).	Matching question to test retention of materials.
L03.05	**Temperature Driving Forces:** Introduces the F_T factor to adjust ΔT_{LM} for multipass configurations, and demonstrates how configuration is selected to ensure acceptable value of F_T. The segment ends with an example exercise for the student (12.5 min).	The student is supposed to solve the assigned exercise on his/her own before watching the next segment.
L03.06	**Solution to Example Exercise:** The correct answer to the previous exercise is presented, to be compared with the student's (4.5 min).	Cluster of three intermediate-level MC questions.
L03.07	**Heat Transfer Coefficient:** Reviewing theory on how to calculate the overall heat transfer coefficient (13.5 min).	Cluster of three basic-level MC questions.
L03.08	**Pressure Drops:** Reviewing theory on how to calculate the tube- and shell-side pressure drops (10 min).	Cluster of two intermediate-level MC questions.
L03.09	**Iterative Design:** Explains that the design procedure is iterative because fluid velocity affects both the required heat-transfer area to be minimized, and pressure drops to be kept within accepted limits (3.5 min).	Cluster of two intermediate-level MC questions.
L03.10	**Example Design (Part 1):** Demonstration of first iteration of the design procedure (Part 1, 13.5 min).	Design-level MC question.
L03.11	**Example Design (Part 2):** Demonstration of first iteration of the design procedure (Part 2, 13 min).	Design-level MC question.
L03.12	**Example Design (Part 3):** Demonstration of subsequent iterations of the design procedure, performed automatically using MATLAB, ending with an animation showing how the final design is actually constructed (14 min).	Intermediate-level MC question.

Technion's VSS is Panopto Analytics®, which logs both viewing times and repeat views of each of the tracked video clips for each student. Using this logged information, one computes the lesson engagement (LE), which is defined as the ratio of each student's viewing time of the lesson's video segments and the total running time of the recorded video segments. Clearly, LE values under unity imply either incomplete lesson viewing, or the viewing of lessons at accelerated rates (students can view video segments between half and twice the regular speed). In contrast, LE values above unity imply multiple views of some of the lesson segments, even if viewed at higher-than-normal speeds, and therefore indicate a more serious review of the material. Multiple views of video segments can be confirmed by the view count, also available from Panopto Analytics.

EXPERIENCES AND LESSONS LEARNED IN THE FIRST LOCKDOWN SEMESTER

As this was the third of the author's courses to move to flipped format,[26] considerable experience had already been acquired in preparing pre-recorded lessons using Camtasia and generating online lessons using Moodle, in which the lesson video segments are embedded. Furthermore, the students were used to that format as they had taken two flipped courses with the author in the previous semester. This left running effective class meetings, ensuring student collaboration, and motivating students to take online learning seriously as the primary new challenges of the semester. More specifically, several challenges imposed by the pandemic needed to be addressed by both the lecturer and his students — some technical, some social, and some a combination of both. These are listed next, together with an account of how they were addressed.

Social Challenges

- *Ensuring that the student teams work together effectively despite social distancing*. The biggest problems experienced in the first pandemic semester were those associated with cooperative learning and project work by the students. The degree to which the team managers were up to the task of marshalling cooperative work between the team members made a big difference to the thoroughness of the reported work in the Final Delivery, as did the move to flipping, in which all staff-student time was reserved for student-team activities with the course staff acting as mentors. The degree to which team members contribute to the deliverables expected from each team needs to be tracked and followed up by course staff to ensure that all are fairly contributing. Furthermore, the individual grade component, which constitutes 10% of the final grade, is decided by the team members themselves, so some level of internal control was in place.
- *Coping with pandemic stress and lack of human live contact*. This issue is related to the previous one mentioned. The degree of stress caused by the lack of human contact affected all students to some degree. It is reasonable to expect that as online education becomes more prevalent, the initial shock effect will wear off as will the degree to which this stress will affect students. Course staff time should be allocated each week for one-on-one Zoom sessions for students on request.

Technical Challenges

- *Learning to use Zoom effectively for online teaching/learning*. Using Zoom is relatively easy, and by the end of the semester the students were sufficiently proficient to enable them to give polished, clear presentations that were very well received by the international panel of evaluators. Lectures were available online, and so Zoom was only used for the exercises, online consulting, and group meetings. Having these activities online had the main disadvantage that some students chose to remain passive, with their video cameras and microphones turned off. This cannot happen in an F2F class meeting. The following actions were found to be helpful to increase the degree of student involvement in class meetings and active tutorials:
    - *Preparing class activities that foster student involvement*. These can include addressing assignments by groups of students working collectively, to posing quizzes driven by applications such as Zoom polls, Kahoot!®, and Socrative®, and using the in-class responses to initiate class discussion.
    - *Encourage students to get involved in classwork*. Course staff should migrate between breakout rooms and act as mentors and cheerleaders to stoke interest in the solution of exercises. The impact of praise and encouragement as a boost to course outcomes was pointed out by Bloom.[1]
    - *Encourage students to attend class meetings with their cameras and microphones turned on*. Turning off one's video camera may be necessary for some students who do not have access to high enough bandwidth to support video communication or who do not have available space for learning at home; it could also indicate a lack of commitment to engage. However, a student who does not activate his/her microphone in addition to a closed video link is choosing not to engage. In any case, this makes it more difficult to connect with the person and reduces the usefulness of the meeting from the point of view of the instructor.
- *Examining students reliably online*. The lockdown was fortuitously eased at the end of May, making it possible to run the Proficiency Exam for this course on campus. Although not required for this course, in another course taught by the author in the first Pandemic Semester, an online exam was necessary. After overcoming teething problems, tested protocols are now in place to enable reliably proctored, fair, and effective online exams, namely:
    - The proctoring requires the student body to be separated into smaller groups (20 students per exam room is a reasonable load), each of which is supervised by at least one proctor, and run on its own Zoom link.
    - There are basically two types of online exams:
        - Closed-book exams involving multiple choice or short numerical questions, which can be prepared on the LMS. At the Technion we use *Moodle Quizzes*. It is recommended that the automatic timer be disabled and that exam timing be handled by the proctor.
        - Open-book, open-ended exams, involving handwritten answers, which can be set up appropriately in the LMS. At the Technion we use *Moodle Assignments*, where the student downloads the exam, completes their solution on paper, and is then given time at the end of the exam to scan the solution and upload it to the Assignment Page.
    - Before the exam starts, students sign onto the exam's Zoom link, identify themselves to the proctor, both via PC and, simultaneously, via smartphone. The PC Zoom link should be with live video camera and microphone, whereas the

smartphone link should have the camera turned on and the microphone and speaker turned off (to avoid feedback). The smartphone should be positioned by the student in the student's examination room so that it observes the student's PC screen. The proctor should move all the smartphone links to a separate Zoom Breakout Room, which can be recorded separately (not via Zoom, as Zoom does not allow recording of Breakout Rooms). Both Zoom Rooms and Breakout Rooms should be recorded in *Gallery View.*

- Questions from students can be handled by moving them to a second Breakout Room, where course staff can respond to them.

Challenges Combining Technical and Social Aspects

- *Teaching/studying the course in flipped format for the first time*. The flipped format was not new for any of the students. In this project-based course, the flipped lectures enabled class time to be left free for project work, which had a positive impact on the quality of the projects. Since all the videos are on the Panopto Cloud Server, employing Panopto Analytics makes it possible to contact students who are not sufficiently preparing before class meetings and suggest that they do so. It is important to make efforts to convince the low-engaging students to make efforts to keep up with the course.
- *Nurturing the students' capability to make effective online presentations*. Since all group meetings were run on Zoom, this meant that the students had lots of practice making presentations as part of the weekly progress reports. They had acquired impressive presentation skills by the end of the semester, as confirmed by the excellent impression they made on the international panel of judges.

One of the advantages of holding our meetings on Zoom was that it was possible to invite international guests to attend meetings and, particularly, to participate in evaluating the final presentations of the process packages. This year's final presentations were attended by invited industrial and academic guests from 11 time zones, whose number exceeded the number of students enrolled in the course. In addition to the usual group of local invitees from the Israeli chemical industry and academia, this year's audience also included, among others, Prof. Sergio Kapusta from Rice University, Prof. Warren D. Seider from the University of Pennsylvania, Prof. Rafiqul Gani, who participated from Denmark, Prof. Claudio Scali from the University of Pisa, and Dr. Soemantri Widagdo, who participated from Bali. This year, the panel of judges consisted of nine Israelis and seven international invitees, each of whom was asked to fill in an appraisal form similar to the one presented on pages 639-640 of Seider et al,[20] in which evaluators use rubrics to appraise aspects of the technical content, presentation execution, and visual aids used by the presenters. The average score is computed for each team and factored into the grade given in the "Final project reporting" component.

Furthermore, having experienced and demonstrated that detailed design of complete plants can indeed be performed successfully by teams of individual students working at remote locations from each other, and from different cultural backgrounds, this opens the possibility of setting up teams composed of students from all over the world to work together.

Over the years, the course has been consistently considered a heavy load by the students, which may explain why, given that the course is an elective with an alternative that involves considerably less work, the number of participants is modest. Nonetheless, the feedback from those students who do register is generally good. Here are the only verbal comments from students who took the course in Spring 2020 (keeping in mind that this was the semester in which all contact was virtual):

- "Unusual lecturer, who incorporates up-to-date teaching methods in his lessons"
- "Extraordinary investment in the student"
- "A course whose content at least in part should be taught to all Chemical Engineering students."

Since this course was taught to a tiny cohort of only 15 students, the small class size precludes statistically significant data analysis. From a pedagogic design perspective, the best that could be concluded was qualitative lessons about the teaching approaches that work and those that do not. The most important of these were the need to track students' online activity, as well as to monitor and encourage cooperative learning throughout the entire semester. In the next section we will discuss how lessons learned from these experiences affected course outcomes.

IMPLEMENTATION OF LESSONS LEARNED IN THE SECOND COVID-19 SEMESTER

As in all flipped courses taught by the author, students of the capstone process design course are given credit (the so-called "flipping credit," in this case, amounting to 10% of the final course grade) for completing class preparation assignments in advance of the class meeting. Each week, the class preparation assignment is to watch the weekly lesson's video segments and complete the quizzes. Until the 2020/2021 academic year, this grade depended only on the quiz grade and was not dependent on the time taken to watch the videos. As students are given four tries on each question, and most questions are multiple-choice with usually four possible answers, it is expected that most students should score 100% in these assignments, even if only by persistence. In fact, students can learn effectively by making errors, realizing the reason for errors (assisted by preprogrammed responses), correcting them, and achieving the correct answers.[2] Since the quiz completion times are also logged by the LMS used at the Technion (Moodle), the author noted that some students completed the quizzes in a very short time, in some cases insufficient to read the quiz questions themselves, which suggests random guessing to complete the assignment. After the experiences in the first lockdown semester of Spring 2020, it was decided to change the award policy for "flipping credit" as being the quiz grade conditional on "sufficient time" viewing the lesson video segments. Unknown to the students, just 50% of the total lesson viewing time was used as the credit trigger, provided that all the video segments were viewed, thus accommodating students who choose to view at twice the normal speed.

Table 4 summarizes LE data by course week, comparing viewing statistics for the 2019/2020 academic year with that of the subsequent year. The table shows values for *N* (the number of students who watched the lesson videos ahead of the class meeting), the percentage of the class who did so (%Eng), the LE mean and standard deviation and, finally, the percentages of the total class (N_{tot}) with LE < 0.9, referred to as low-engagers, and LE > 1.1, referred to as high-engagers.

Table 4 highlights the stark difference in student engagement in the two years under comparison. In 2019/2020, when the flipping credit did not depend on lesson viewing time, the percentage of the enrolled students who activated the pre-recorded videos in advance of class meetings varied from 41%-88% (77% on average), with an average of 57% low-engagers. In contrast, in 2020/2021, when students were aware that flipped credit depended on viewing the online lessons, an average of 97% of the class prepared in advance of class meetings in some fashion, with the average percentage of low-engagers dropping to only 13%. It is interesting to note that in Week 2, which was the first week in which online viewing of lessons was required, the initial level of low-engagers was 30% of the class, which was much higher than average. All of the low-engagers were contacted to remind them of the rules,[19] which had an immediate effect on reducing their number. The average percentage of high-engagers in 2019/2020 was only 16%, peaking at 25%, whereas in 2020/2021 the average was 21%, peaking at 40%. Comparing the two years, there is a large drop in the proportion of the class that are low-engagers from 2019/2020 to 2020/2021, but only a modest increase in the proportion of high-engagers. Clearly, it is advantageous to require a minimum attention time to video viewing, but more should be done to encourage students to seriously engage while viewing online lessons.

It would be reasonable to expect lesson engagement to impact the final exam grades. Figure 1 shows the final exam grade distributions for the capstone design course in 2020/2021, in which the distribution of the entire class is compared with the distributions for the 50% most engaged (i.e. the students who had the top 50% average LE values) and

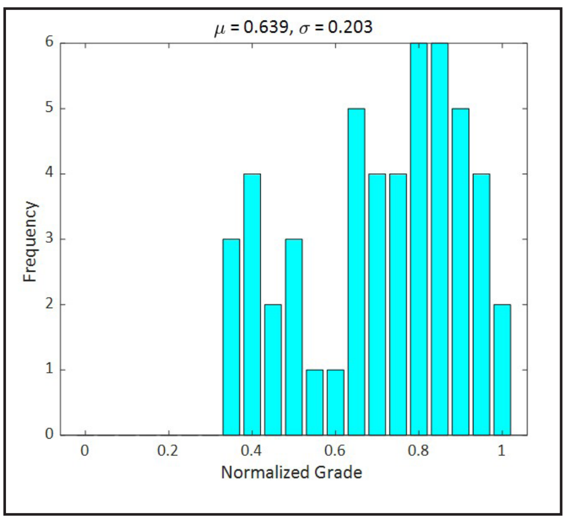
TABLE 4
LE Statistics for the Capstone Process Design Course (2019/2020 and 2020/2021)

	(a) 2019-2020, N_{tot} = 56						(b) 2020-2021, N_{tot} = 53					
Week	**N***	**%Eng**	**μ**	**σ**	**LE < 0.9**	**LE > 1.1**	**N***	**%Eng**	**μ**	**σ**	**LE < 0.9**	**LE > 1.1**
2	42	75%	0.76	0.42	61%	13%	48	91%	0.96	0.22	32%	15%
3	46	82%	0.79	0.53	63%	20%	51	96%	1.05	0.14	13%	32%
4	43	77%	0.63	0.53	73%	9%	53	100%	0.96	0.25	15%	11%
5	47	84%	0.77	0.46	55%	18%	53	100%	1.04	0.12	8%	26%
6	42	75%	0.97	0.37	45%	25%	53	100%	1.07	0.24	9%	25%
7	47	84%	0.93	0.30	43%	23%	53	100%	1.03	0.22	9%	19%
8	49	88%	0.94	0.40	39%	23%	53	100%	1.10	0.24	8%	40%
9	46	82%	0.85	0.43	55%	16%	52	98%	1.03	0.29	15%	17%
10	44	79%	0.80	0.39	61%	13%	51	96%	1.01	0.17	13%	15%
11	45	80%	0.87	0.46	46%	18%	51	96%	1.07	0.24	9%	26%
12	45	80%	0.71	0.42	61%	7%	50	94%	1.00	0.20	15%	13%
13	23	41%	0.82	0.40	79%	11%	51	96%	1.01	0.13	13%	17%
Ave	43.3	77%	0.82	0.43	57%	16%	51.6	97%	1.03	0.21	13%	21%

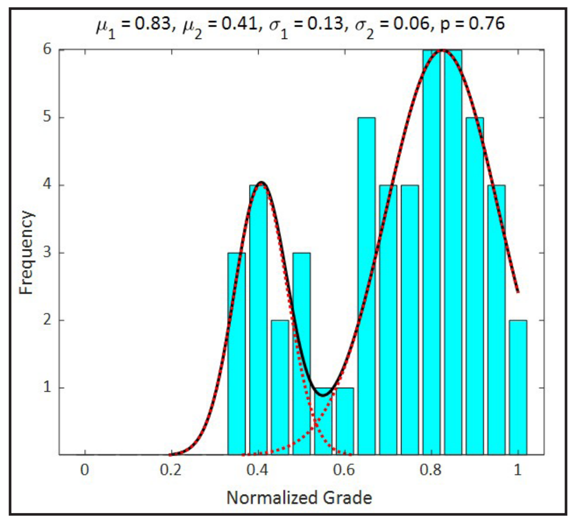
* This number refers to the number of students who watched the lesson videos in advance of the class meeting with LE > 0.5.

50% least engaged students (the rest of the class). Several things are clear:

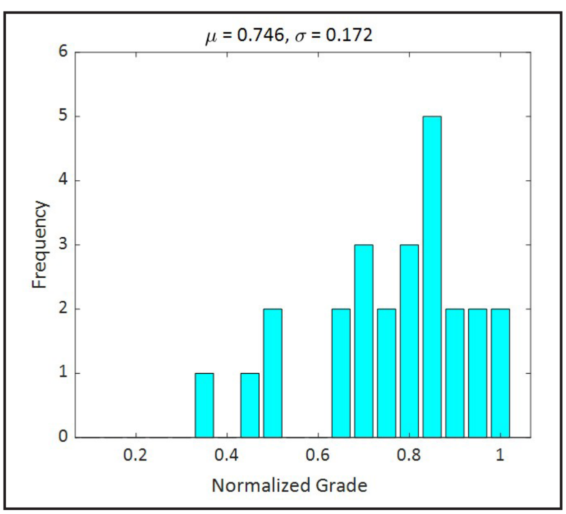
- As shown in Figure 1(a), the class average grade is 69.3%, which is a little on the low side, explained by the fact that 26% of the class (13 out of 50 students) failed the exam.
- As shown in Figure 1(b), the grade distribution can be analyzed using Lewin's approach,[27] in which the parameters of a bimodal distribution model comprising a weighted sum of two normal distributions are fitted to the exam grade distribution, yielding estimates for averages and standard deviations of high- and low-performing subpopulations (μ_1, σ_1, μ_2, and σ_2), as well as the proportion of high-performers (p). In this case, p is estimated as 76%, which is consistent with the actual failure rate of 26%.
- Separate distributions of the grades of the top 50% and bottom 50% lesson engagers are shown in Figures 1(c) and 1(d), respectively, noting that the average grades for the two populations are 74.6% and 63.6%, respectively. The Z-statistic for these two distributions is 2.2, indicating a statistically significant improvement of the high-engagers over the low-engagers, by approximately one standard deviation. This is in line with Bloom's[1] prediction that active learning improves exam grades over those obtained by passive learners by the same margin. It is also noted that of the 13 students who failed the



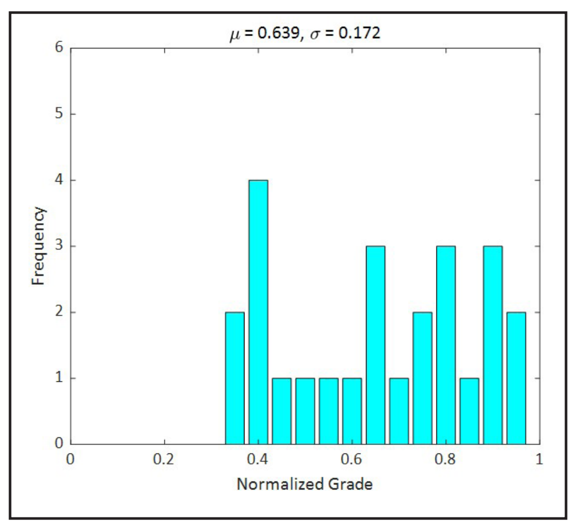
(a) Exam grades of the entire class



(b) Bimodal distribution fitted to exam grades of the entire class



(c) Exam grades of the top 50% of engagers



(d) Exam grades of the lowest 50% of engagers

***Figure 1**. Exam grades for the capstone design class of 2020/2021.*

exam, nine were low-engagers. This indicates that lesson engagement significantly affects the exam performance and is the justification for monitoring LE and continuously encouraging the low-engagers to make more effort to come prepared for class meetings.

DISCUSSION AND CONCLUSIONS

This paper has described the flipped course *Plant Design*, with respect to its learning objectives, course content, and available resources. The course has been taught conventionally by lecturing until the 2018/2019 academic year, with 2019/2020 being the first instance of its offering in flipped format. The switch to flipped format was fortuitous, as online lectures were the necessary requirement due to the COVID-19 lockdown.

The main technical challenges for both the lecturer and the students were how to effectively teach and learn using Zoom. In addition, students were challenged to learn how to effectively collaborate online and to make polished presentations using Zoom, while the lecturer was challenged to run reliable and proctored examinations online. These challenges were successfully addressed by the experience acquired in the duration of the semester. A reliable protocol was put in place that enabled proctored online exams to be handled in both closed-book, multiple-choice, and open-book, open-ended formats.

In contrast, the social challenges were more difficult to completely resolve. These included the difficulties associated with teamwork constrained by social distancing and coping with the pandemic stress. The bottom line is that while the lockdown imposed by the pandemic created challenges, the lessons learned were that acceptable outcomes are achievable in this environment.[15,18] Having learned to teach flipped classes completely online using streaming technology such as Zoom opens avenues hitherto not considered.

Online teaching in the second COVID-19 semester (the winter of 2020/2021) harnessed the lessons learned in the first pandemic semester. We have discussed especially how monitoring each student's learning engagement from the start of the semester impacts their degree of engagement throughout the semester, which in turn impacts the final course outcomes. In the spirit of ICAP principles,[3] it is desirable to also monitor students' class and active tutorial activities and categorize the degree to which these activities are "passive," "active," "constructive," and "interactive," with the objective being to proactively raise the cognitive level of student activity to promote learning. This categorization will direct all future offerings of the design sequence courses at the Technion, whether the class meeting will be F2F or online on Zoom, with a stronger focus placed on outreach to the low-engagers to encourage them to participate.

To summarize, here are the most important takeaways based on the author's online teaching experiences from the first two semesters of the COVID-19 pandemic, which also largely apply to teaching F2F in a regular class setting:

1. Class time with the lecturer should not be wasted on lecture delivery, but it is better used to foster problem solving and cooperative learning activities, with the expectation that students prepare for classes by studying online modular study materials (video clips and associated activities such as quizzes).
2. It is worthwhile for the lecturer to invest some time in the preparation of these study materials, as these can be reused from year to year, and are extremely valuable to all students, and especially to those who take their learning seriously.
3. Students' online study of the modular learning materials needs to be monitored to ensure as many as possible of the students are using the materials correctly and are actually learning. It is recommended that this activity be assigned modest credit dependent on adequate coverage of the materials, dependent on adequate time-on-task.
4. For courses involving group projects, the degree of cooperation between student group members needs to be monitored. Again, modest credit should be assigned to students' efforts on behalf of the group's work, which can be regulated by the students themselves.

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