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Teaching PSE mastery during, and after, the COVID-19 pandemic

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ABSTRACT

After more than a year of online teaching resulting from the COVID-19 pandemic, it is time to take stock of the status quo in teaching practice in all things concerning process systems engineering (PSE), and to derive recommendations for the future to harness what we have experienced to improve the degree to which our students achieve mastery. This contribution presents the experiences and conclusions resulting from the first COVID-19 semester (spring 2020), and how the lessons learned were applied to the process design course taught in the second COVID-19 semester (winter 2020) to a class of 53 students. The paper concludes with general recommendations for fostering active learning by students in all PSE courses, whether taught online or face to face.

1. Introduction

Process Systems Engineering (PSE) aims to harness computational methods to improve the design, control, and operation of processing systems. Suppose a processing system leads to the product distribution shown in Fig. 1, where a value of 70% is the minimum quality required for saleable product. Clearly, a production line in which a third of all production is unsellable would be totally unacceptable. In the same way, if we were teaching a course for which the same plot shows the students' final exam grade distribution, we should be equally unhappy, as one third of our students would not have achieved course mastery.

Most of us have experienced over a year of "lockdown teaching" because of the COVID-19 pandemic, forcing us to move our teaching activity exclusively online. The objective of this paper is to take stock of the status quo after this period, and to derive recommendations for the future to harness what we have experienced to improve the degree to which our students achieve mastery in all things PSE. The author has been teaching PSE courses to undergraduates at the Technion, the Israel Institute of Technology, for more than 30 years, evolving his teaching to active learning methods and in the last seven years, to the "flipped class" model. In the spring of 2020, teaching became particularly challenging, since it was taught online for the first time, with students having to collaborate remotely with each other also for the detailed design work.

In the rest of this introduction, we review the status of engineering education and explore the literature concerning active learning and its impact on online teaching and engineering education. Graham (2018) conducted a study on the global state of the art in engineering undergraduate education on behalf of MIT's *New Engineering Education Transformation* (NEET) initiative, charged with developing and delivering a world-leading program of undergraduate engineering education at that university. The study is based on interviews with 178 individuals with in-depth knowledge and experience of world-leading engineering programs and identifies the top ten institutions that are acknowledged as "current leaders" and the top ten considered as "emerging leaders" in engineering education. Of those, only five institutions appear on both lists: Olin College, Technical University of Delft, University College London (UCL), National University of Singapore (NUS), and Chalmers University Sweden. The report also lists the program and institutional features that distinguish these global leaders and identifies the challenges that constrain global progress. An important lesson from the study is the common denominator in the more successful programs which feature chains of courses which implement active learning that is student-centered, rather than individual stand-alone efforts. The report also postulates future directions for the engineering education sector, identifying three potential trends: (a) the shift in the center of gravity of the world's leading engineering programs from high-income countries to the emerging 'powerhouses' in Asia and South America; (b) a move towards student-centered curricula and multidisciplinary learning; and (c) the emergence of a new generation of leaders in engineering education that deliver integrated student-centered curriculum

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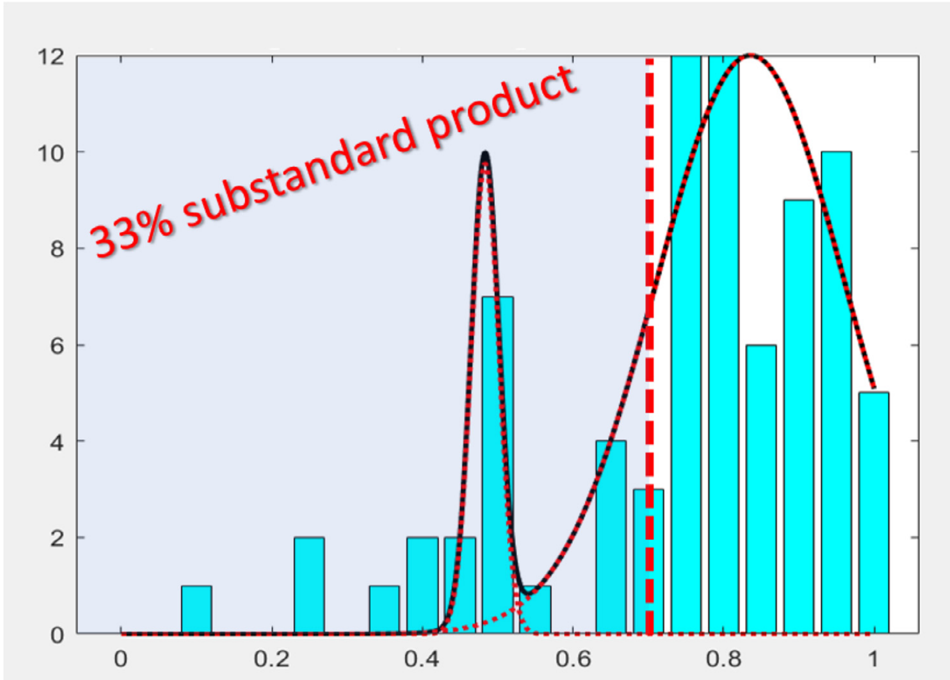

Fig. 1. An undesirable product quality distribution.

at scale. One good example is UCL, where the first and second years of all engineering departments follow six cycles of learning, each culminating in an immersive and formative week of group project activity (Tsatse and Sorensen, 2021).

After three semesters of lockdown teaching, most of us are indeed teaching 100% online, by necessity. Lewin et al. (2022) present the results of a survey mapping PSE teaching perceptions and practices, that returned the positions of 82 academic lecturers from around the world, mostly with at least 10 years of experience in teaching PSE topics. Lewin et al. (2022) report an even split between those who teach in the traditional teacher-centered method (teacher talks – students listen) and those who apply student-centered, active learning in their classes, mostly by those teaching process design rather than other PSE topics. At the author's university (the Technion, Israel Institute of Technology), most of the exercises/recitations are also delivered synchronously by teaching assistants (TAs), where they deliver additional lectures rather than use the meetings as an opportunity to activate students. Thus, for the most part, we are not using available technology to make learning more effective. Instead of moving at least some of the lecture materials online and require students to cover them as preparation, and then use at least part of the available staff-student contact time to foster active learning, this opportunity is largely being squandered. We are mostly lecturing, with our students mostly passive, and as well established, passive students learn less. As sadly pointed out by Miller (1922):

"*Lecturing is that mysterious process by means of which the contents of the notebook of the professor are transferred through the instrument of the fountain pen to the notebook of the student without passing through the mind of either.*"

Unfortunately, we discover how little some of our students have learned at the end of each course, when final exam distributions are often similar to that shown in Fig. 1. Of course, by then it is too late to fix the problem. And just as it was pointed out by that pioneer of active learning, Eric Mazur (Rimer, 2009):

"*Just as you can't become a marathon runner by watching marathons on TV, likewise for science, you have to go through the thought processes of doing science and not just watch your instructor do it.*"

Another take on the same idea, as pointed out by Lewin and Barzilai (2021), is:

"*Watching their teaching assistant demonstrating how typical exercises are solved is about as useful to students as going to the gym and watching how their gym instructor lifts weights for them…*"

Although Benjamin Bloom is most known for his taxonomy Bloom et al., 1956, he contributed much more. For example, as postulated by Bloom (1968), the degree to which students achieve mastery depends on four conditions: (1) Clear definition of what constitutes mastery; (2) Systematic, well-organized instruction, focused on student needs; (3) Assistance for students when and where they experience difficulties; (4) Provision of sufficient time for students to achieve mastery. Two desirable key features follow from the spirit of Bloom's ideas:

(a) One should support the acquisition of knowledge and skills mastery by creating opportunities for active learning. In this regard, consider the ICAP categorization of cognitive learning patterns proposed by Chi et al. (2018), which delineates the degree of decreasing learning effectiveness, from Interactive, Constructive, Active, to Passive.
(b) Learners should be encouraged to experiment, even if they make mistakes or even fail (Kapur, 2015). Learning is all about trying, failing, understanding why they have failed, trying again, and repeating these steps as necessary.

Opportunities for students to engage in active learning and experimentation require allocating sufficient staff-student contact time, time that in a conventional setting is taken up by lecturing. This reallocation can be realized by implementing a "flipped classroom." In the "flipped classroom," home and class activities are "flipped," that is:

(a) What used to be class activity, that is, lecturing by teachers, is moved to home activity to be completed by students in advance of class meetings with teachers. This home activity consists of a combination of pre-recorded lectures, readings, online quizzes, and other individual assignments.

(b) What used to be homework, that is, exercises, computational assignments, and some of the project work, are moved to class activity, to be performed individually or in groups by students, with lecturers and TAs present in mentor and guide roles.

Thus, the main justification to move to flipped format is the desire to increase the proportion of the student-staff contact time in which students are actively learning rather than just listening to lectures (Crouch and Mazur, 2001; Felder, 1995; Felder and Brent, 2015).

In another important contribution, Bloom (1984) reports the modes of learning that improve outcomes, with the most significant obtained by 1–1 (teacher-student ratio) personal tutoring, which increases the degree of mastery as exhibited by exam grades up to two standard deviations higher than for students taught conventionally by a lecture-based approach. Clearly, personal tutoring is not a sustainable pedagogy, with a more typical teacher-student ratio being 1–30. In a course with that teacher-student ratio that is taught in a teacher-centered approach, the contact time between the teacher and the students is mostly utilized for lectures by the teacher, often with modest involvement of the students. In recitations, the assistant will often take the same approach. This means that in a teacher-centered approach, students are largely passive in most of the contact time available, with the students expected to take an active role mostly when tackling homework sets on their own. These deficiencies reduce the degree to which students acquire mastery in higher-level design and evaluation capabilities. In contrast, in a student-centered approach with the same teacher-student ratio (1–30), the contact time is focused on giving opportunities for students to become involved in class activities, with the teaching staff acting as mentors. Amongst the activities are class quizzes leading to discussions, brainstorming, cooperative problem-solving, and student presentations. By nurturing student involvement, the teacher can better assess the degree of mastery being built up by the students. Student involvement is even more critical in the recitations, where the focus should be on giving students time to work problems for themselves. For students to learn, they need to be given opportunities to make mistakes, understand the reasons for the mistakes, and correct them. This takes time, and the more recitation time taken up by the TAs explaining their problem-solving strategies, the less time the students will have for their own efforts. Mentoring students' work, should fill most of the recitation time, enabling staff to mentor and assess student capabilities.

This formative assessment can only be ascertained if the teachers and assistants reduce the amount of time that they are lecturing in favor of providing time for active learning by the students (Freeman et al., 2014; Velegol et al., 2015). Since "flipping the classroom" inherently frees class time, it is one way to make this happen. In a recent study, Munir et al. (2018) presented results for the successful implementation of a flipped class incorporating cooperative learning to a small class of graduate students.

This paper is organized as follows. PSE mastery is best defined in terms of the instructional objectives of each course. Hence, Section 2 provides a clear statement of the learning outcomes for the three key PSE areas: numerical methods, process control, and process design. Next, in Sections 3 and 4, the flipped paradigm as applied at the Technion's Chemical Engineering Faculty is described, and then quantitative evidence is presented indicating that there is significant improvement in the outcomes obtained by students who engage with the course, over those that do not. Next, Section 5 lists some of the challenges imposed by implementing flipping online imposed by the pandemic, as well as the lessons learned on how to address them. Finally, Section 6 provides a road map to facilitate this change by employing the "flipped classroom," in which part or all the materials that were previously lectured in class time are provided asynchronously as video-lectures, for the students to cover ahead of class meetings as preparation. The main message of this paper is the clear need to free class time to enable students to actively engage in their own learning.

2. Typical instructional objectives for PSE mastery

Most of us in the PSE community will agree about the importance of taking a systems approach in chemical engineering design and analysis instruction (Cameron and Lewin, 2009; Silverstein et al., 2013; Cameron et al., 2019). Within the framework of PSE, this instruction would include at least courses in the central expertise areas of numerical methods, process control and process design. Curricula for these courses are best expressed as instructional objectives, which link learning objectives to learning outcomes – indeed, the course definitions are couched in terms of learning outcomes, as demonstrated for the PSE courses listed below. Because PSE largely deals with problem-solving, the most important and relevant levels of Bloom's (1956) taxonomy that students need to master are the highest: *analysis*, *synthesis*, and *evaluation*. A helpful way of teaching these materials is by making use of concept maps, which facilitate explaining the connection between the course components. An example of a concept map for a course on numerical methods is presented in Fig. 2. The key PSE concepts and their instructional objectives are listed next.

2.1. Numerical methods

This course ideally instructs the students in the understanding of the basic building blocks of numerical methods, before continuing to provide tools for their practical application. On the completion of such a course, students are expected to select the appropriate numerical methods for a given problem, implement them, and interpret the obtained results. Typical course outcomes are as follows:

Building blocks:

- Efficient solution of linear systems
- Finite difference approximations (derivatives, interpolation, integration)
- Efficient solution of nonlinear systems
- Mastery in unconstrained (gradient methods) and constrained minimization (Linear Programming)

Applications:

- Linear and nonlinear regression capabilities
- Efficient solution of ordinary differential equations, initial-value partial differential equations, and boundary value problems
- Integrated problem-solving capabilities

2.2. Process control

This course provides the tools to develop first principles and empirical process models, and then using the derived models, to design simple control systems to meet desired closed-loop performance. Typical course outcomes (Seborg et al., 2004) are as follows:

Process modeling:

- First-principles modeling capability
- Ability to generate state-space and transfer function models
- Block diagram manipulation capability
- Ability to analyze the transient response of linear systems

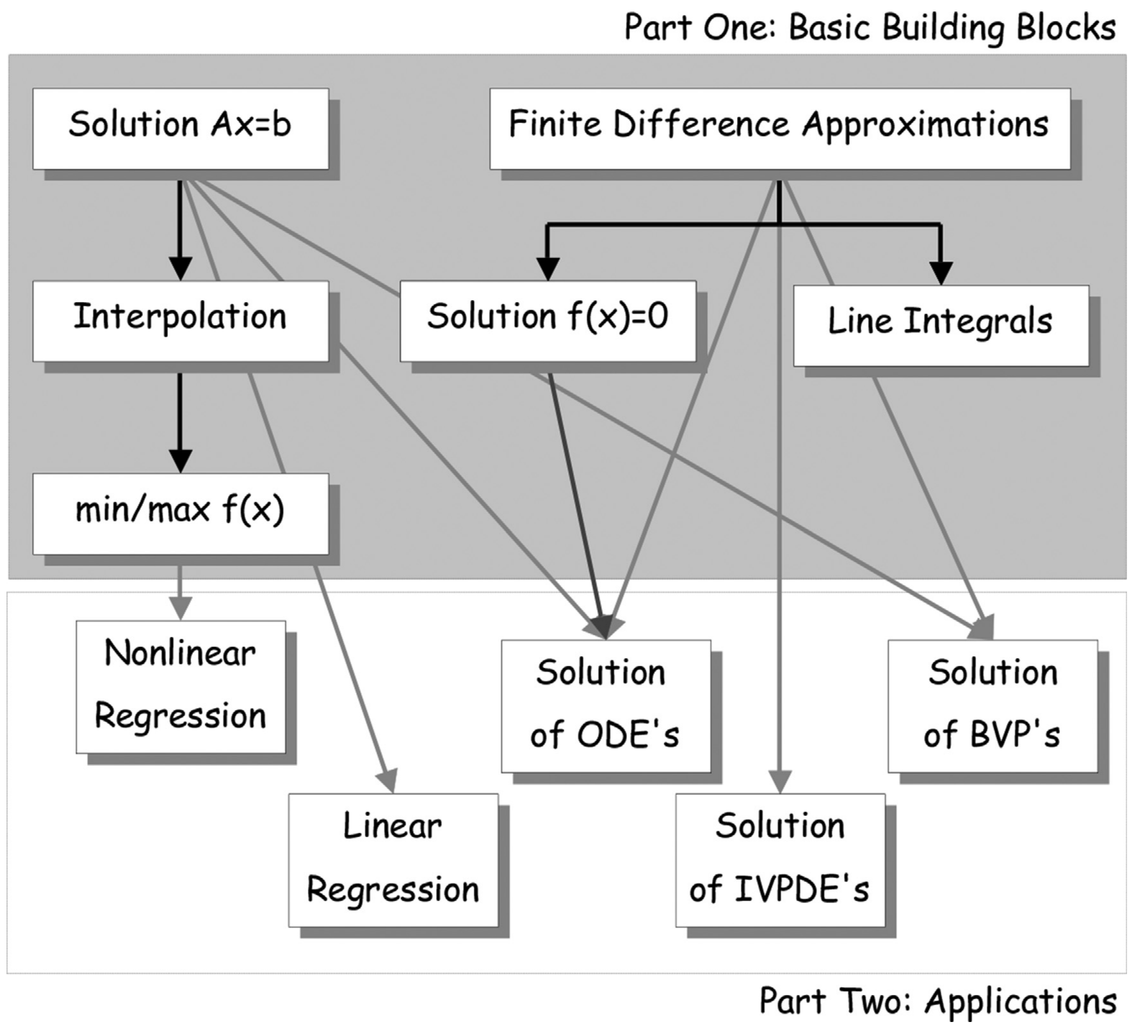

Fig. 2. Concept map for a typical course on numerical methods.

Process control synthesis:

- Frequency domain analysis capabilities
- Stability analysis capability
- Capability to synthesize control systems to meet response specifications using the root locus method
- Knowing how to tune PID controllers effectively
- Capability to design cascade and feedforward control systems

2.3. Process design

The capstone design course represents the acid test of students' ability to apply the engineering tools they have acquired from the core courses studied previously, with typical desired outcomes (Seider et al., 2017) being as follows:

- Capability to carry out plant costing and profitability analysis
- Separation sequence synthesis capability for both zeotropic and azeotropic systems
- Capability to perform maximum energy recovery (MER) targeting and heat exchanger network (HEN) synthesis
- Plant-wide control system configuration capability
- Capability to perform a qualitative hazard and operability study (HAZOP) and to carry out a quantitative hazard analysis (HAZAN)
- Proven cooperative design project capability, demonstrating both team and individual skills

As an example of a typical design project, consider the best team effort submitted for the 2020/21 challenge, which involved the design of a process for the manufacture of 90k Tons/year of DME from a feedstock of methanol, presented in Fig. 3, which achieves a venture profit (VP) of $6.8 million/year. In the reaction section of the plant (Fig. 3a), methanol feed is mixed with recycled methanol from the separation section, heated in E-100 with intermediate pressure steam to partially vaporize the methanol, and then heated using hot reactor effluent in E-101 to superheat the methanol vapor fed to the reactor to its optimal temperature. The reactor methanol conversion is below equilibrium, only 74%, a result of plant-wide optimization to maximize the VP. Note that about half of the energy required to be transferred to the methanol feed is recovered from the hot reactor effluent, leaving the rest to be used to power the reboilers of the separation system. Again, this is a consequence of plant-wide optimization. Moving on to the separations section of the plant (Fig. 3b), we note that the methanol recycle purity is only 84%, and that heat recovered from the hot reactor effluent provides most of the reboiler duties for both columns in the separation system (87% of the reboiler duty required for the first tower and 100% of that required by the second tower, respectively). Both these features are a consequence of plant-wide optimization to maximize the VP. This example illustrates the kind of mastery expected from our students.

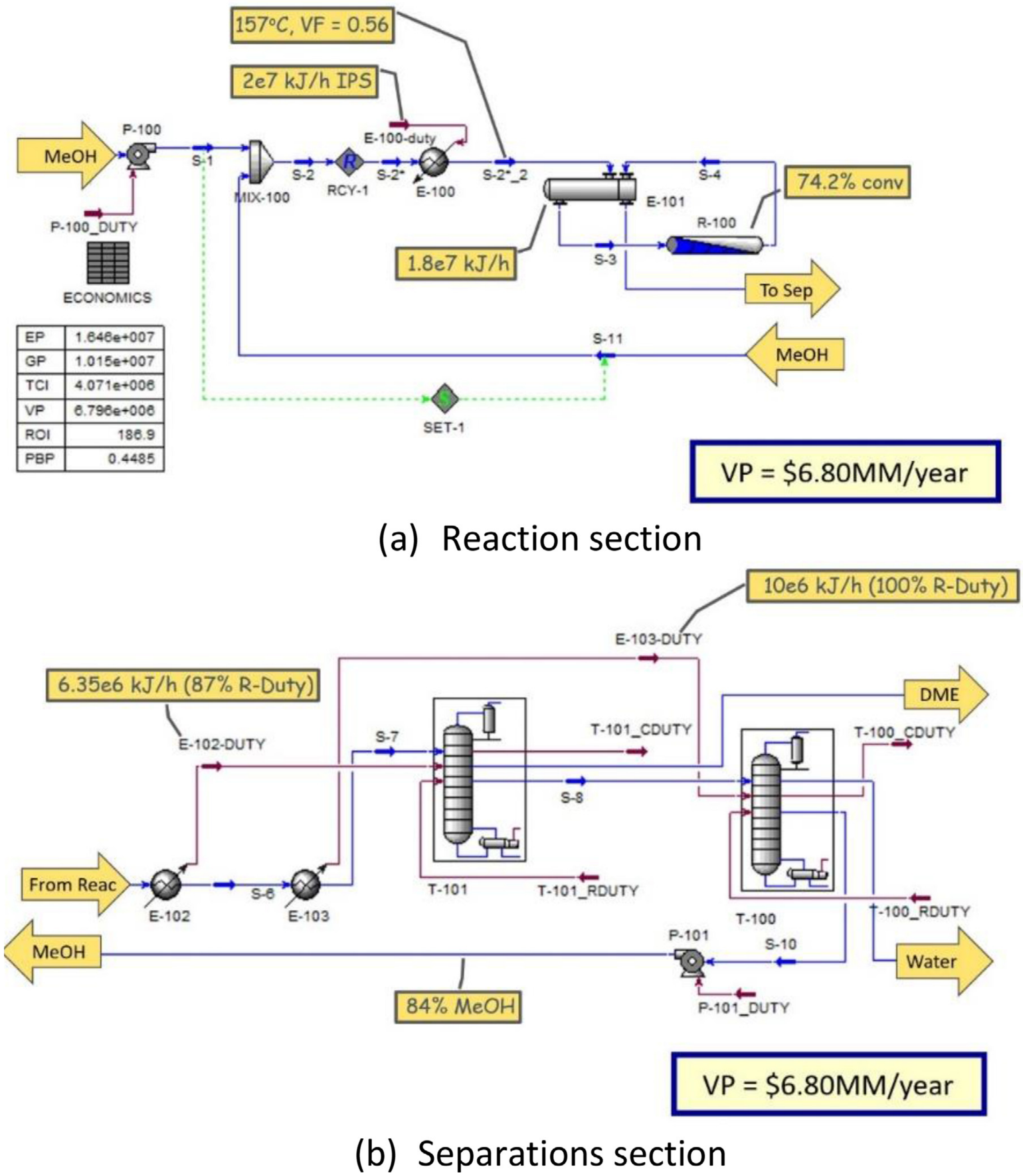

Fig. 3. The best student team solution for a process to manufacture DME from methanol.

3. The flipped class paradigm as implemented at the technion

Our implementation of the *flipped classroom* involves the following sequence of activities, repeated in every week of each course (See Fig. 4):

a *Online Materials* – Produced by converting lectures to pre-prepared, online lessons composed of 5–15 min video clips interspersed with online activities. Students are expected to cover these materials on their own as homework in advance of each week of activity and are given course credit for it. **Benefits:** Students learn the basic materials covered in each week at their own pace, and their learning is reinforced by addressing the online activities as they follow the materials. The online activities can be tailored to achieve specific objectives in each stage of the course. These can be: (a) Regular quizzes**:** Quiz questions posed as multiple-choice, matching, or numerical computations; (b) "Your turn" extended calculations and small-scale designs**:** A problem for the student to tackle independently is defined at the end of a video clip, which is followed by a video clip in which a possible solution to the problem solved is presented, which students can compare to their solutions; (c) Preparing for brainstorming**:** A video clip can present a problem that requires group effort to address, for which students are requested to collect information, write down ideas, and bring their results to class for discussion in groups. Note that all these activities increase the students' stake in their learning and will prepare them to make better use of the next resource – the Class Meeting.

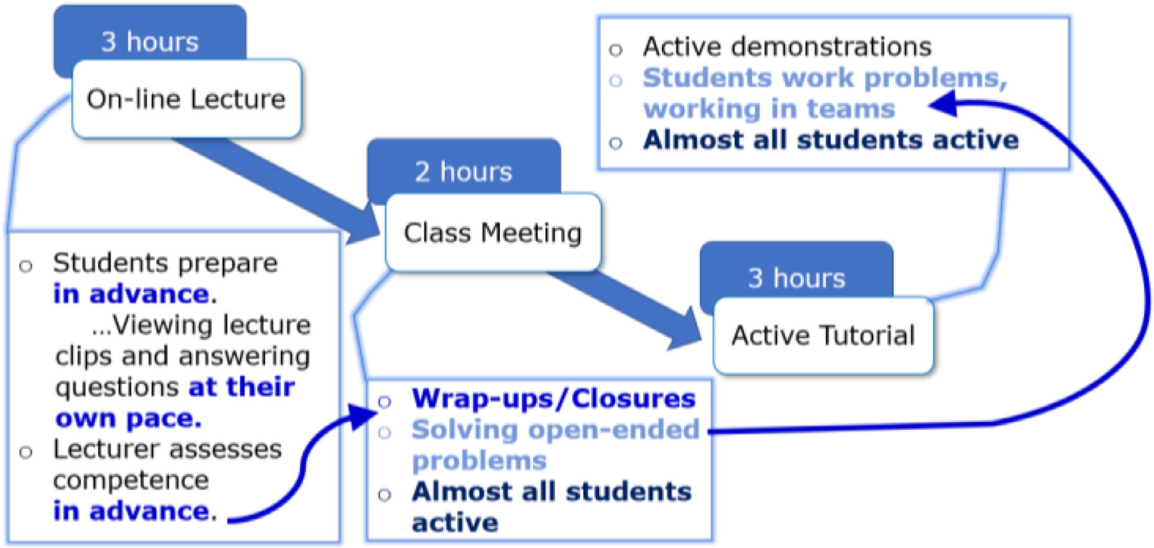

Fig. 4. Weekly schedule of our flipped courses.

b *Class Meetings* – Moving from *teacher-centered lecturing* to *student-centered meetings in the classroom*. A typical class meeting combines quizzes, class discussions and open-ended problem solving, with the focus being to keep the students active. **Benefits**: Giving students the opportunity to prepare ahead increases their effective participation in class and impacts positively on the degree to which they learn and master the application of what they have learned. The specific benefits of each type of activity that could be utilized are as follows: (a) Quizzes for comprehension: These could be clicker questions, to test comprehension of concepts learned at home, or to reinforce previous, related materials. The lecturer can check the level of understanding exhibited by all the students in real time; (b) Quizzes to generate discussion: When the questions raised may have more than one solution, it pays dividends to use them to generate class discussion. Learning from incorrect answers is often more valuable than focusing only on correct ones; (c) Open-ended problem solving: This is one of the main reasons for having class meetings. The focus should be on getting students to participate in the development of solutions. For particularly complex problems, dividing the class into separate workgroups may have benefit. For online synchronous class meetings on Zoom, for example, it is recommended that classes be divided into breakout rooms.

c *Active Tutorials* – For students to master course content, they need to apply themselves to independently work problem sets covering the curriculum. The job of the teaching assistant in this setting is to be the enabler for student efforts rather than a demonstrator of solutions. **Benefits:** In active tutorials, students working in teams solve the classwork (previously referred to as homework) in class time. This ensures that: (a) All students who participate in the sessions are actively involved in working problems; (b) Assistance can be provided by staff and from students, helping each other; (c) Students, assistants and the lecturer all receive feedback in a timely fashion (in real time).

The most important take-away from implementing this sequence is that at every phase of the week's activities, students optimize their time-investment in the course; at home, they use their time to build their basic knowledge, whereas in their contact-time with staff they hone this knowledge to higher levels by application and practice. These improvements are difficult to achieve in a conventional lecture-based approach for several reasons: (a) If students come to a lecture unprepared, they will find it difficult to simultaneously absorb what is new material as well as participate actively in meaningful Q&A; (b) Lecturers who plan to cover a given set of materials in class may be left with insufficient time to allow for more than modest Q&A.

The home preparation required of the students in the flipped class paradigm releases class time for work with the students at higher levels. For example, consider the three-week segment of the process design course covering heat exchanger network synthesis, detailed in Table 1. In the seventh week of the course, students are introduced to MER targeting using the temperature interval (TI) method, and basic HEN design rules, with typical class exercises involving MER targeting and HEN designs for relatively simple systems involving two hot and two cold streams. By the eighth week, the students will have learned to use more advanced techniques, such a stream splitting and dealing with threshold problems as well as reducing the number of heat exchangers to the minimum necessary, making it possible for them to tackle more complex problems, involving four or more hot streams transferring heat to four or more cold streams. By the ninth week, they will have learned how to reliably extract stream data from process flowsheets, and how to integrate reactors and distillation columns into flowsheets to minimize total utility demands using the grand composite curve (GCC), thus empowering them with the ability to practically apply the HEN synthesis procedure to complete flowsheets.

Some readers may be surprised by the focus only on pinch methods for HEN design instruction rather than the use of MILP/MINLP approaches. It is certainly true that HEN synthesis, can be carried out efficiently for small/medium-sized problems using MILP/MINLP. For a graduate-level course, attended by students who have received a comprehensive undergraduate chemical engineering degree, and therefore grounded in engineering principles and insights, the usage of optimization methods for HEN synthesis is indeed appropriate. The main advantage of teaching pinch design methods to undergraduates is the *physical insights* they gain as a consequence. This insight is lacking if one simply formulates the design problem as a linear/nonlinear program. It is therefore recommended that if one is teaching undergraduate process design, the focus on teaching **only** optimization methods for HEN synthesis should be reconsidered.

All these topics were taught with the same allocated time before flipping was instigated in the process design course, but after

Table 1
Subjects and concepts taught and exercised in the three-week sequence between weeks 7 and 9 in the course that covers HEN design.

Week	Subject	Concepts	Typical Exercises
7	Introduction to HEN Design	Composite Q-T Curves MER targeting; Basic HEN synthesis principles.	TI Method for MER targeting; Basic HEN MER design (matching rules at the pinch) on 2H2C (two hot and two cold streams) problems.
8	Advanced HEN Design	Loops, and loop breaking Stream splitting Threshold problems.	Complex HEN problems (e.g., 4H4C) requiring multiple stream-splitting.
9	Heat and Power Integration	Data extraction from flowsheets; the GCC; Heat integration of reactors, columns, heat pumps and heat engines.	Applying the technology to real process streams; HEN design with multiple cold and hot utilities aided by the GCC; Heat integration of distillation column trains.

introducing flipping in the course, a higher level of mastery can be achieved by students because the freed lecture time is now used for practical application and practice.

Whether this potential benefit results in improved summative outcomes is determined by the final examinations, and we will get to that later. While moving to active learning has benefits, it is by no means a panacea, and is subject to some negative repercussions, as pointed out by Felder (1995), most of which can be offset if the instructor is open-minded and responsive to the concerns of students:

a *Dealing with student resistance*. Flipping may be new to the students, so it is important to set the stage in the first meeting, which should not be used to cover technical material but rather, should describe the teaching methodology and its benefits, making clear to students what is expected of them and how they can make the best use of the time they are willing to invest in the course. It is basically “Flipping 101,” if you will.
b *Providing value-added content in class meetings*. A teacher of a course driven by active learning is a mentor and coach rather than just being a transmitter of information. Investing class time in coaching is an important and worthwhile activity. Introducing mini clinics in class meetings constitutes productive use of contact time.
c *Maintaining focus on student-needs*. One should listen to the students and be sympathetic to their perceived difficulties. This does not mean that standards need to be compromised, but rather one should use the communication as an additional way to teach the students to take on responsibility for their own learning.
d *Maintaining the right attitude as instructors*. One should always be patient with one’s students, particularly when some of them take longer than expected to achieve the learning objectives. Eventually, most of them will achieve them, especially if one does not relax those objectives.
e *Remaining optimistic, tempered by realism*. One should aim high but not expect 100% success. There will always be a hopefully small group of die-hards who resist active methods, and a hopefully small percentage of students who, despite best efforts by the course staff, do not achieve mastery. Often the two groups share many members.

Thus, a fair question would be whether all the effort entailed in implementing active methods are worth the investment. The costs involved are obvious: flipping implies the preparation of video clips based on the lecture materials as well as formative activities, usually quiz questions, that accompany each clip, which may require considerable one-time investment of effort on the part of the instructor. Furthermore, not all the students take kindly to its implementation. Does it make that much difference to the learning outcomes?

4. Is it worth it to flip the class?

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 2020/21 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. Since the quiz completion times are also logged by the learning management system (LMS) used at the Technion (Moodle®), it was noted that some students complete the quizzes in such a short time, in some cases insufficient to read the quiz questions themselves. After the experiences in the first lockdown semester of Spring 2020, it was decided to change the flipping credit award policy as being the quiz grade conditional on “sufficient time” viewing the lesson video segments. A measure of the students’ viewing time for each online lesson, the *Learning Engagement*, LE, is defined as:

LE = a student’s viewing time/total viewing time of all the segments of the same lesson.

An associated measure is the *Video Engagement*, VE, defined as:

VE = number of video clips access by a student/total video clips in all lesson segments.

It is of note that LE and VE are correlated – invariably, values of LE greater than unity are accompanied by values of VE over unity, meaning multiple views of portions of the same video clips. Granted, students could turn on each video clip and just leave them running unattended. However, it is unlikely that this is the common practice for several reasons: (a) Students would have to be extremely uninterested in learning to click on 7–12 video clips of 5–10 min each to just get minor credit; (b) Since the average number of video views per lesson is greater than the number of videos per lesson, why would the average student click the same videos twice, just to get credit?; Most crucially, (c) If the practice of not paying attention to the video lessons is extensive, how is the correlation between LE and exam outcomes explained, noting that most of the exam failures were of students with low LE scores?

Table 2 summarizes LE data by course week, comparing viewing statistics for the 2019/20 academic year with that of the subsequent year, reporting 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

Table 2
LE statistics for the capstone process design course (2019/20 and 2020/21).

	(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.

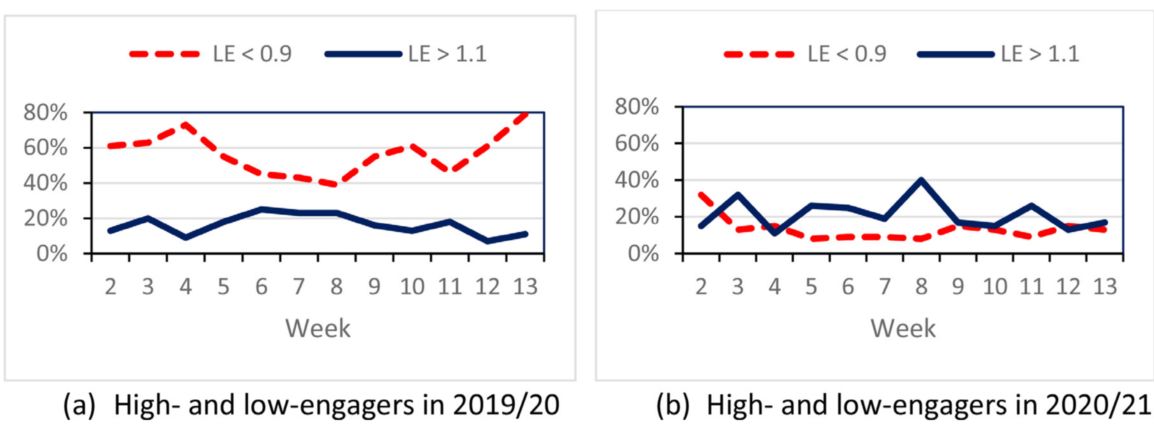

Fig. 5. Comparison of percentages of high-and low-engagers by week in the classes of 2019/20 and 2020/21 enrolled in the capstone design course.

LE< 0.9, referred to as low-engagers, and LE> 1.1, referred to as high-engagers Fig. 5. compares the class percentages of high- and low-engagers for the two consecutive academic years: 2019/20 and 2020/21, using data from Table 2.

The data in Table 2 and Fig. 5 highlight the stark difference in student engagement in the two years under comparison. In 2019/20, when the flipping credit did not depend on lesson viewing time, the percentage of the enrolled students that viewed the pre-recorded videos in advance of class meetings varied from 41 to 88% (77% on average), with an average of 57% low-engagers. In contrast, in 2020/21, 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 the percentage of low engagers 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, much higher than average. All of the low-engagers were contacted to remind them of the rules, which had an immediate effect on reducing their number in the remainder of the course. The average percentage of high-engagers in 2019/20 was only 16%, peaking at 25%, whereas in 2020/21 the average was 21%, peaking at 40%. Looking at the plots for the two years shown in Fig. 5, one observes a large drop in the proportion of the class that are low-engagers from 2019/20 to 2020/21, 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 clearly more should be done to encourage students to seriously engage while viewing online lessons.

But how does lesson engagement impact on the final exam grades? Fig. 6 shows the final exam grade distributions for the capstone design course in 2020/21, in which the distribution of the entire class is compared with the distributions for the 50% most engaged (i.e., the students that had the top 50% average LE values) and 50% least engaged students (the rest of the class). Several things are clear:

(a) As shown in Fig. 6(a), the class average exam 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.
(b) As shown in Fig. 6(b), the exam grade distribution can be analyzed using the approach of Lewin (2021a), 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%.
(c) Separate distributions of the exam grades of the top 50% and bottom 50% lesson engagers, are shown in Fig. 6(c) and 6(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 (1984) prediction that active learning improves exam grades over those obtained by passive learners by the same margin.

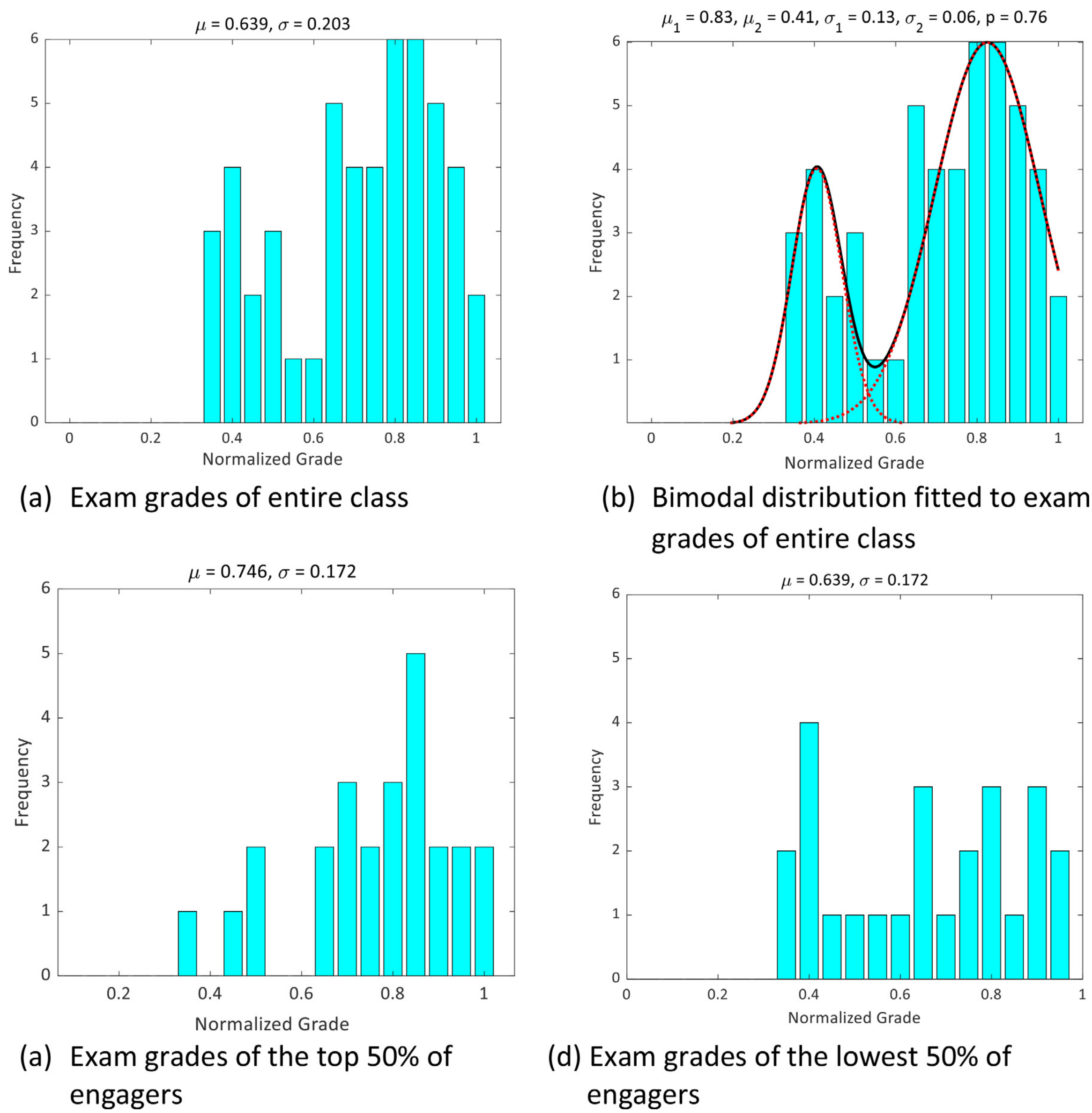

Fig. 6. Exam grades for the capstone design class of 2020/21.

It is noted also that of the 13 students who failed the 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. Clearly success in the final exam does not just depend on LE, but they are correlated.

Given these outcomes, which may be typical in many PSE courses, it is appropriate to define the responsibilities of the stakeholders in the classroom. Educators have the responsibility of preparing and presenting well-organized course materials, and it is the responsibility of the students to apply themselves as adults, to learn and to master the course subject. That distinction is clear. The educator has other responsibilities though, for example to excite, encourage and motivate the students to better efforts. And we do have a product as teachers, whether we agree about it or not. Our products are students whom we graduate who are a credit to themselves and their alma mater. If a student does not make the grade, it is also our duty not to pass them. At the Technion, each student can sit the final exam of each course twice. The grade distribution presented in Fig. 6 was for the first exam of the design course in 2020/21. The total failure rate of the class after the second exam with the same degree of difficulty as the first, was much lower (Just 2 students – 4%).

Finally, a word on the effect of other factors on the course outcomes is in order. Lewin and Barzilai (2022), using multiple linear regression, studied the effect of in-course factors such as lesson engagement (LE), as defined previously, and active tutorial attendance, and out-of-course factors, namely the students' GPA on the exam grades of both the process design and process control course, as taught at the Technion. For both courses, the most significant effect was that of the GPA, indicating that the students' general preparedness is the most important factor. The second important effect was attendance of the active tutorial. In addition, for the process control course, LE also had an effect on the outcomes, although its effect was found statistically insignificant for the design course.

5. Online challenges and how to address them

The spring of 2020, with the resulting COVID-19 lockdowns, introduced additional challenges to effective teaching. Several problems surfaced, associated with a need for social distancing and online lessons (Chakraborty et al., 2020; Chhetri, 2020; Ghasem and Ghannam, 2021). Here is an itemized list of problems together with the ways that have been found helpful in overcoming them:

a Undesirable online behavior of students, such as students turning off cameras and microphones or passive and/or low student attendance. **Fixes:** (a) Request that students turn on cameras with microphones on mute, turning on microphones to participate. A bright and positive attitude by the lecturer will go far in securing cooperation of the students. (b) What worked outstandingly well was to invite all the students to an online "BYOB (bring your own bottle) Party" before the start of classes, to get to know them and to use the informal meeting as a chance to share expectations. After that, the ice was broken and most of the students were cooperative in the online Zoom sessions. Attendance was high (usually over 70% of the students), with many students participating in class discussion.
b Undesirable online behavior of teachers, such as the teacher talking most of the class time, or teachers demonstrating solutions of problems, with little involvement of students, or allowing a few students to dominate the in-class discussions. **Fixes:** (a) Pause in presentation to give students a chance to ask questions. Respond to the questions and check that the response fully-addresses them; (b) In-class problem solving should involve the students. Do not provide full solutions up-front but get students to contribute suggestions and partial solution steps by brainstorming with student involvement; (c) Use online quizzes to promote class discussion, with all students participating. Use polling software to involve the whole class in this, and use the class answers, especially the wrong ones, to generate discussion in the class.
c Too many students (15–25% or more if uncontrolled, less than 15% if monitored and feedback corrections applied) not preparing for the synchronous meetings by studying the online lessons in advance. This rests of the assumption that all the enrolled students are willing to participate and interested in the course; in reality, many of them are not enrolled in compulsory PSE courses, or even the chemical engineering program, because of their personal choices. Whatever the reason, for them to succeed in passing the PSE courses, engagement as requirement needs to be made clear to all enrolled students. We should be concerned with the *consequences* and not the *reasons* for non-engagement, and how we as teachers can encourage engagement. **Fix: You cannot afford to lose 15–25% of the class!** Not taking steps to bring these non-performers back into the fold can mean a large proportion of under-performers who do not even pass a course. Efforts need to be made to track the non-collaborators, reaching out to them from the start of the course and bringing them back in. This is surprisingly easy to do if the teacher takes a supportive rather than critical stance in the outreach message. Many of the otherwise non-cooperative students will take kindly to a teacher's outreach, especially if the communication is positive and focused on how much the teacher cares about their success. If the percentage of students truly on-board is maintained high during the entire course, the whole class will benefit, and the outcomes at the end of the course will reflect this (Lewin, 2021b).

Most of these suggested fixes will work in a regular, face-to-face (F2F) setting also.

6. A flipped roadmap for the future

The author has had a long and successful experience with the effective implementation of the flipped classroom to the teaching of both process control and process design, now for seven consecutive years. There is evidence for improved outcomes in process design instruction resulting from the implementation of active methods (Lewin and Barzilai, 2021). In the year of the pandemic, and the consequently imposed lockdowns, the flipped classroom was relatively easily adapted to online learning (Lewin, 2021b). The experiences gained in the second semester of the pandemic with a relatively large group of students who took the process design course have led to a clear conclusion that a correctly implemented flipped paradigm is highly effective, and particularly so for students who take an active role in their learning. This implementation involves the following eight key components:

1 *Have a game plan*. Balance expectations of the lecturers, teaching assistants and students, as all three stakeholder groups need to be on board. It is recommended that a lecturer with no previous experience in flipping try the paradigm first on a single week of class, selecting the week that is the most challenging to fully-cover using a conventional approach. In addition to preparing the online lesson as homework, the class meeting and the active tutorial should be included in this trial.
2 *Preparation of online lessons*. Define instructional objectives for each lesson. Divide the lecture into video segments of between 5 and 15 min duration, ensuring that the content is complete (e.g., cover all steps in a mathematical development, remembering that unlike in a regular lecture, students are not able to ask questions if any step is unclear to them). Write and use a script when recording the video segments and practice the delivery before recording. Audio quality is more critical than video quality.
3 *Preparation of effective quiz questions*. Follow each video segment with a quiz question/activity to test students' understanding. Write useful explanations of all answers (especially important for the wrong ones) and allow students to retry the questions that they get wrong. This is not a test – it is part of their learning!
4 *Lesson assembly and testing*. Upload questions and videos and generate a Moodle lesson (or similar). The teacher should test the flow and system response first, and have an assistant perform an independent check.
5 *Require students to complete the lessons before Class Meetings*. Students should be given credit for this crucial preparatory step, with the credit awarded to students being conditional on their adequate coverage of the material. Continuously follow up on students who do not prepare adequately, starting from the first week of the semester.
6 *Plan for a useful Class Meeting*. Prepare additional materials and do not repeat what the students have already learned online. The following is a partial list of activities that have been found to be useful: (a) Short quiz questions – to be used to foster class-discussion; (b) Open-ended exam-style questions to be solved with class participation; (c) Project/ design work, executed in "break out rooms." To make this activity effective, it is important to plan sufficient time for the "break-out" activities, and to schedule a summarizing discussion in class when the students return; (d) Short student presentations.
7 *Schedule an Active Tutorial*. Schedule sufficient time as this activity largely replaces what used to be "homework." Allow time to discuss solution strategies in class. Divide the class into small work groups, using breakout rooms if online, or by ensuring appropriate seating arrangements if F2F. Make sure that the question levels in each week's problem set span from easy to difficult (exam level), and make solutions available online. It is unreasonable to expect students to master exam-level questions that integrate course topics in the final exam without giving

them the opportunity to practice on similar questions for themselves in the Active Tutorials during the semester.

8 *Follow up on every component*. All three steps of the flipping paradigm are critical to success and all of them can be continuously improved. For the Online Lesson, were there any problematic video segments, and were there any problematic or particularly useful quiz questions, and should more questions be added? For the Class Meeting, were there enough students active, and how many attended? Were the planned activities suitable? For the Active Tutorial, how many students attended, and how many of them were actively engaged and completed the assignments?

The online version of our Flipped Classroom implementation assumes that all students have access to internet of sufficient bandwidth, especially when it comes to class meetings and active tutorials, and this can indeed be an obstacle to expanding the usage of the method. Internet penetration is not equal around the world, where the penetration rates can be as high as 96%, such as in the USA and in South Korea, and as low as 65%, such as in Mexico. However, the prevalence of active teaching methods such as flipping does not necessarily rely on penetration rates as high as those in the USA. NUS in Singapore, for example, is a world leader in the implementation of active teaching, where the internet penetration rate is only 88%.

7. Conclusions

This paper presents the case for better utilizing the familiarity with online technology to motivate PSE educators to make the switch to employing active learning in the classroom, as leverage for improving the degree of mastery of more students. Some limitations of this presentation are in order. This paper has focused on the teaching of PSE subjects, which is in the scope of the author's experience. While there is no reason why active methods should not be applied throughout the chemical engineering curriculum, and indeed in other disciplines too, this is out-of-scope of the paper's stated intentions. The paper has also not addressed many important social and emotional aspects of student life on campus, which were disturbed in many ways by the outcomes of the pandemic. These issues, too, are largely out of scope of the paper's focus, given that the main objective was to suggest suitable teaching approaches for the future.

Long experience with the flipped-class approach indicates that engagement with the materials throughout the semester improves the students' level of confidence in their mastery of the subjects. These observations could explain the improved performance in the final exams in the process design course since adopting active learning and flipping (Lewin and Barzilai, 2021). The encouraging outcomes suggest that this format can be taught equally well both online and in F2F teaching, and that active learning methods achieve better results in both cases. Hopefully, these findings and recommendations will encourage others in the PSE community to move to active learning methods.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Daniel R. Lewin reports a relationship with Technion Israel Institute of Technology that includes: employment, speaking and lecture fees, and travel reimbursement.

Author Contribution Statement

Daniel R. Lewin is the sole author of this contribution.

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