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Teaching PSE Mastery During, and After, the COVID-19 Pandemic

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Abstract
The author has been teaching process systems engineering (PSE) courses to undergraduates at the Technion for more than 30 years, evolving his teaching to active learning methods, and in the last five years, to the “flipped class” model. In the spring of 2020, teaching became particularly challenging, since it was taught on-line for the first time, with students having to collaborate remotely with each other also for the detailed design work. This contribution presents the experiences and conclusions resulting from the first COVID-19 semester (spring 2020). At the time of writing, the recommendations are being implemented on two flipped courses, on process design and process control, which are being taught completely on-line in winter 2020 to the same class of 53 students. The presentation will thus summarize the lessons learned over a complete year of practice.

Keywords: Process design instruction, process control instruction, project-based learning, active learning, flipped classroom, on-line learning.

1. Introduction – typical instructional objectives for PSE mastery
All of us in the PSE community will agree about the importance of taking a systems approach in chemical engineering design and analysis instruction (Silverstein et al, 2013). 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, composed of curricula like those listed below. 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 Figure 1. Representative learning outcomes for these three key courses are outlined next.

1.1 Numerical Methods: This course ideally instructs the students in the understanding of the basic building blocks of numerical methods, before continuing to providing tools for their practical application. On the completion of such a course, students are expected to select the appropriate numerical method for a given problem, implement it, and interpret the obtained result. 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 and constrained minimization (Linear Programming)
Applications:
- Linear and nonlinear regression capabilities
- Efficient solution of ODEs, IVPDEs and BVPs
- Integrated problem-solving capabilities
1.2 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 modelling:
- First-principles modelling capability
- Ability to generate state-space and transfer function models
- Block diagram manipulation capability
- Ability to analyse the transient response of linear systems

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

1.3 Process Design: The capstone design course represents the acid test of a student’s ability to apply the engineering tools he/she has acquired, 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 MER targeting and heat exchanger network synthesis
- Plant-wide control system configuration capability
- Capability to perform a HAZOP and to carry out a HAZAN
- Proven cooperative design project capability, demonstrating both team and individual skills
2. Student-centered vs Teacher-centered teaching

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. Bloom reports the modes of learning that improve outcomes, with the most significant obtained by 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.

In a course that is taught in a teacher-centred 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-centred 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-centred approach, 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 will be able to 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 TA explaining his/her 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 favour of providing time for active learning by the students (Velegol et al, 2015). One of the best ways to make this happen is to transition to flipped classes, which move a large part of the information transfer to on-line, pre-recorded lectures, which the students need to complete as their homework in advance of class activities. The flipped classroom, involves the following sequence of activities, repeated in every week of each course:

a. **On-line Materials** – Produced by converting lectures to pre-prepared, on-line lessons composed of 5-15 min video clips interspersed by on-line quizzes. 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 on-line activities as they follow the materials. The on-line 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 movie 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 groups discussion. 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.

b. **Class Meetings** – Moving from *teacher-cantered lecturing* to *student-cantered 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 of the students, instantly; (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 in separate workgroups may have benefit.

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).

### 3. On-line 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 on-line lessons. Here is an itemized list of problems together with the ways that have been found helpful in overcoming them:

a. Undesirable on-line behaviour 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 of the students to an on-line “BYOB 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 on-line Zoom sessions. Attendance was high (usually over 80% of the students), with many students participating in class discussion.

b. Undesirable on-line behaviour 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 on-line 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 (typically 15-25%) not preparing for the synchronous meetings by studying the on-line lessons in advance. **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 underperformers who do not even pass a course. Efforts need to be made to track the non-collaborators, reaching out to them from Week 1 of the course, and bring them back in, and it is surprising how easy this is to do. Many of them will take kindly to your outreach, especially if your communication is positive and focused on how much you care 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.

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

4. 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, 2020a). In the year of the pandemic, and the consequently imposed lockdowns, the flipped classroom was relatively easily adapted to on-line learning (Lewin, 2020b). The experiences gained in the second semester of the pandemic to a relatively large group of students who simultaneously participated in courses in process design and process control have led to a clear conclusion that a correctly implemented flipped paradigm is highly effective. 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 on-line lesson as homework, the class meeting and the active tutorial should be included in this trial.

2. **Preparation of on-line lessons.** Define instructional objectives for each lesson. Divide the lecture into video segments of between 5–15-minute duration, ensuring that the content is complete (e.g., cover all steps in a mathematical development). 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/cluster/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. Continuously follow up on students who do not do this, 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 on-line. 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”; (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 on-line, or by ensuring appropriate seating arrangements if F2F. Make sure question levels in each week’s problem set span from easy to difficult (exam level), and make solutions available on-line. It is unreasonable to expect students to handle exam-level questions well in the final exam without giving them the opportunity to practice solving 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 On-line 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?

5. Conclusions

Experience with the flipped-class approach indicates that engagement with the materials throughout the semester improved the students’ level of confidence in their mastery of the subjects. These observations could explain the improved performance in the final exams in both the process design and the process control courses since adopting active learning and flipping in both. The encouraging outcomes obtained in both courses suggest that this format can be taught to good effect in more than one course at a time, and equally well both on-line and in F2F teaching. Hopefully, these findings and recommendations will encourage others in the PSE community to move to active learning methods.

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