EFFECT OF UNIT OPERATIONS LABORATORY COURSE STRUCTURE ON LEARNING AND SELF-EFFICACY

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In the chemical engineering curriculum, the unit operations laboratory course traditionally serves several key roles in the development of students as professional engineers. In a recent survey of U.S. chemical engineering programs, over 75% of responding programs cited the following course objectives for their unit operations laboratory: (1) practice data analysis, (2) practice effective teamwork, (3) demonstrate laboratory ethics, (4) exercise creativity within an engineering context, (5) become familiar with appropriate instrumentation, (6) design an experiment, and (7) identify strengths and weaknesses of theoretical models as descriptors of real-world outcomes.[1] Other sources not only echo these objectives, but additionally emphasize teaching skills such as technical communication and critical thinking, among others.[2-5]

The structure and implementation of the laboratory course will necessarily have a significant impact on the extent to which these skills are developed. In particular, the use of open-ended laboratory activities, as opposed to narrowly defined "recipe"-style activities, seems to be particularly critical for learning and thinking skill development, as shown by several studies in chemical engineering unit operations courses. One previous study suggests that the use of "ill-posed problems" in unit operations can improve teamwork, critical thinking, and problem-solving, and that active engagement of the students in the problem-solving process can improve retention, decision-making, and self-directed learning.[2] Similarly, another unit operations study discusses how inquiry-oriented activities with troubleshooting, feedback, and discourse with an instructor can also improve critical thinking and goal-setting.[3] Other work has indicated that an experimental design approach with open-ended problems leads to increased student learning and performance when compared with an approach using traditional "recipe-style" laboratory activities.[4]

Broadly, these types of open-ended lab activities with ill-posed problems fall under the category of problem-based learning. Problem-based learning is roughly defined as a technique in which teachers act as facilitators, posing authentic, ill-structured problems to students such that the students must determine the problem's key issues and their own knowledge gaps, and then perform the work to fill in those knowledge gaps and solve the problem (which may have multiple solutions).[6] According to a meta-analysis, problem-based learning has been shown to be beneficial on a broad scale, due to increased student motivation and satisfaction (vs. traditional learning methods), as well as enhanced skills such as self-directed learning, problem-solving, and self-evaluation.[6] Woods' review lists other benefits, including deeper learning, higher knowledge retention, and development of career skills such as teamwork, confidence, and lifelong learning.[7] Theorists have noted that these beneficial characteristics are likely due to the social nature of the learning that occurs (following Vygotsky's social constructivist theory) in which the task involves active engagement, authentic tasks, application of knowledge in multiple representations, and learning communities.[8-9]

Furthermore, problem-based learning methods compare favorably with the skills necessary for graduating engineers, as identified by ABET, Inc. in outcomes 1-7 of Criterion 3.[10] For example, outcome 6 is written as "an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions", which connects directly to an open-ended laboratory approach. Similarly, outcome 1 requires "an ability to iden-

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tify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics", which coincides directly with providing student teams with "ill-posed problems". Although these outcomes do not require a laboratory experience to be fulfilled, open-ended laboratory courses can powerfully address these outcomes in addition to their other benefits described above. From these sources, an open-ended approach would seem favorable for learning on multiple fronts.

Focusing on more affective benefits, similarly active approaches such as senior engineering capstone courses have been shown to aid specifically in the development of student self-efficacy, or a student's personal beliefs about his/her ability to learn and achieve success at various tasks.[11] Numerous studies have shown that engineering students' self-efficacy can be directly linked to academic success and persistence,[11-13] and self-efficacy has even been linked directly to student career choice.[14-15] Mamaril et al. recently validated an instrument to measure students' self-efficacy in relation to engineering.[16] The instrument is broken down into sub-scales to assess students' beliefs about their general capabilities and specific types of skillsets important to engineering (e.g., experimental skills, design skills). Each subscale is assessed with four or five Likert-style statements about which students rate their certainty.

In this study, the unit operations laboratory course at a mid-sized private university was redesigned to incorporate problem-based learning so as to encourage development of the skills and self-efficacy described above, as well as increase student learning and engagement. In addition, the new course included an emphasis on communication skills and teamwork, both of which are critical career skills and also match well with ABET, Inc. outcomes 3 and 5.[10] Other course changes were also made to the lecture schedule and methods of faculty feedback. In the fall of 2016 and 2017, students were surveyed before and after the course to determine if any improvements were made in their engineering self-efficacy. At the end of the course they were also surveyed as to their perceived achievement of the learning objectives, which aspects of the new course contributed most to their learning, and how the course could potentially be improved.

A version of this work was previously published in the *Proceedings of the ASEE 2017 Annual Conference*.[17] The current work has been enhanced by the addition of an additional year's worth of data. The results and discussion have been updated to reflect the larger collective set of data and comparisons between the two semesters' responses.

COURSE CONTEXT AND DESCRIPTION OF COURSE CHANGES

At this university, the unit operations course is typically taken in the fall of the senior year. At that time, the students will have taken fluid dynamics, separations, and mass transfer, and they will take reaction kinetics concurrently. Senior design (capstone) is not taken until the spring of senior year. Additionally, in the current curriculum, the unit operations laboratory is often the students' first significant engineering-focused laboratory course. In revising the course, several approaches were taken in an effort to increase the development of literature review skills, critical thinking, communication, and experimental skills, as well as to expose the students to more "real-world" experiences. Changes to the course structure were focused on several key areas: open-ended problem-solving with structured teamwork, an emphasis on communication skills, active faculty feedback based on standard rubrics, and minimization of lecture time. The revised course was co-taught by two faculty members. One of the instructors had been teaching the course for several years. The second faculty member had pedagogical expertise in chemical engineering, and collaborated with the existing instructor to make the course revisions.

Open-Ended Problem-Solving

In the prior version of the course, students completed three single-session lab activities on the unit operations of pumps/piping, distillation, and gas absorption, and they watched short demonstrations of several other unit operations. For the lab activities, they were provided with detailed instructions for obtaining data necessary to calculate various characteristic values for each unit operation (e.g., mass transfer coefficient, friction factor), and their assignment was simply to complete these calculations and fill in a worksheet. Anecdotally, the first author noted that during the lab activities, the students would attempt to complete the instructions as quickly as possible, spending little time analyzing and reflecting on the unit operation or the meaning of their own actions. For the demonstrations students did not interact personally with the equipment in any way. They merely watched a teaching assistant (TA) point out important parts of the equipment, which was not always turned on.

The course revisions utilized a more problem-based learning approach. For each of three unit operations, students were given a semi-ambiguous set of goals (e.g., characterize the relationships between boilup rate, pressure drop, heat loss, and overall column efficiency) and three four-hour lab sessions with which to find the necessary data to complete the goals. All of the unit operations were framed within the context of a "real-world" situation (e.g., gas absorption to reduce CO_2 emissions) so as to increase student engagement and "buy-in". A complete example of these instructions for the pump and piping project is shown in Figure 1. Additionally, instructions were provided on how to operate the equipment, but not necessarily on how to obtain any of the necessary data. It was up to the student teams to review the theory behind the operation of the equipment, research standard analysis methods, and develop safe experimental protocols to find the necessary data to achieve the goals set out by the instructors.

Structured Teamwork

In previous versions of the course, students were randomly assigned to teams and instructed to take on roles to divide up the necessary tasks. However, these roles were never enforced by the instructor or the TAs, and, anecdotally, the first author noted that most students disregarded the roles entirely.

In the revised course, students were randomly assigned to small teams and rotated through defined roles. Responsibilities were divided up so that each role would focus on a separate aspect of the project. For example, the Team Leader was responsible for time management, overall report formatting, learning the primary theory, and making the final presentation as a representative for the entire team. The Experimental Engineer, on the other hand, was responsible for ensuring safe operation of the equipment and designing the in-lab experimental work. Finally, the Analyst was put in charge of the data and error analysis. Rotating roles served several purposes: first, this helped to divide up the work which helps eliminate "squabbles" among teammates about workload balance; second, it helped ensure that each team member experienced each type of activity (versus, for example, one team member always performing the data analysis because they are "good at it"); finally, the inclusion of roles allowed the instructors to more fairly assign grades among team members, which is especially important in the case of a "slacker". For grading, each part of the report was divided up by role, so if one team member did not properly complete their section of the report, the other team members would not get penalized as much as they would in a more traditional grading system (i.e., where everyone receives the same grade). Detailed rubrics are available upon request from the first author.

Emphasis on Communication Skills

Previously, students were required to complete short pre-lab assignments for each lab activity containing basic conceptual questions on the unit operation in question. Following the lab activity, students filled in a worksheet with the relevant data. For the demonstration-style activities, the students were given previously obtained data and required to write a report analyzing the data and the unit operation. All assessments were graded by graduate student TAs, but feedback was generally neither timely nor detailed. Writing skills were not assessed in any formal or consistent manner, if at all, and students were given no opportunity to practice oral presentation skills.

In the revised course, the student teams were assessed based on a short pre-lab memo, a full lab report, and an oral presentation given by the Team Leader. For the pre-lab memo, the teams would need to review the most critical information about their unit operation, including the principles of operation, safety concerns, and critical equations for data analysis; this would help the students prepare for their lab work. The oral presentation would be given only by the Team Leader to encourage teamwork and to imitate a "real-world" experience in which a manager might need to be responsible for his or her entire project.

THE SITUATION

You are an engineer working for Enterprise Pharmaceuticals, which has recently developed a new drug, Inaprovaline, which will be used for medical resuscitation. Part of the production process involves pumping water from its main reservoir to a mixing tank downstream. In order to save money, Enterprise Pharmaceuticals wants to install either one or two centrifugal pumps into its pre-existing piping network (described in detail below). As the plant engineer, it is your job to determine whether the available pumps (whose performance is still completely uncharacterized – the manufacturer cannot provide this information for some reason) will be sufficient. In addition, you have also been asked to characterize the accuracy of an old flowmeter and determine where in the plant layout it should be placed.

YOUR ASSIGNMENT

You have at your disposal an identical pump setup to the one you are trying to use as well as a piping rig that contains a sample of every type of pipe and fitting you will encounter in the plant between the water reservoir and the holding tank. ***This piping rig is very different from the one in the plant. The rig has "samples" of each of the pipes and fittings, but the layout is completely different from that in the plant.*** Using this setup, you need to do the following:

- Characterize each of the centrifugal pumps alone, both in series, and both in parallel by creating a set of pump performance curves (similar to what you might be given by a pump manufacturer)
- Determine the parameters for optimal efficiency in all three pump arrangements based on the pump performance curves
- *For your specified piping layout*, characterize the frictional head loss for each of the fittings and piping types, and calculate the estimated head loss vs. flowrate for the total layout. Also calculate the available net positive suction head (NPSH).
- *For your specified piping layout*, determine the most appropriate pump arrangement (centrifugal pump alone, in series, in parallel) and under what operating conditions this arrangement is feasible. You should consider pump performance, capital and operating costs, and/or any other metrics of interest when making your evaluation. If none of the arrangements are appropriate, describe what changes should be made to the layout so that one of them can work.
- Measure flowrate using one of the flowmeters (specified in your layout description). Compare its measurements to the flowrates indicated by the software, and determine where in your company's piping layout it should be placed.
- To validate your results, compare your experimental data to correlations, values, and data found in the literature.

The details of your company's pump/piping layout and which flowmeter to characterize are described at the end of the document.

For this lab, you are also required to include a to-scale diagram of your assigned pump/piping layout (the one described on the last page) in the "Apparatus" subsection of your lab report. You should follow the guidelines for formal engineering schematics, as described in class.

Figure 1. *Example of context and semi-ambiguous goals provided to students, taken here from the pump and piping project. Other projects' assignments available upon request.*

Faculty Feedback

In the past, the course was taught by one professor who would occasionally check in on the students during lab (to make sure that things were running smoothly), but did not necessarily engage the students in any meaningful way. As mentioned above, grading of assignments was performed by TAs who often did not provide useful or timely feedback.

The revised course was co-taught by two faculty members. As part of every single lab session, at least one instructor would check in and interact with the student teams, answering any questions and offering guided questions to help them succeed in their tasks. However, guidance was often kept purposely "vague" to encourage independent thinking and self-directed learning from the students.

Furthermore, reports and presentations were graded by both faculty members based on detailed rubrics in an effort to standardize grading across groups and to better communicate instructor expectations. Each rubric included a focus on formatting and communication skills in addition to theory and data analysis. All rubrics, as well as a detailed writing manual, were made available to students at the beginning of the semester through the course website and were strongly advertised through a lecture early in the course that focused on instructor expectations and rationale for those expectations. Feedback was provided on all presentations within a few days of the presentation by returning the completed rubrics along with typed comments. All written reports were provided with detailed corrections and feedback about writing style and formatting, and report revisions (to earn back lost points) were encouraged for the first pre-lab and full lab report. The instructors made an effort to return graded reports in a timely manner so that the feedback could be used to improve the next report. In the first year of the two-year study, most reports were returned at least several days before the due date of the next report. Unfortunately, in the second year grading got behind schedule, and was not always returned with enough time for students to use the feedback effectively.

Minimization of Lecture

Previously, the course included weekly lectures on topics relating to the unit operations lab activities as well as other topics relating to working with equipment in industry. Due to the rotating nature of the lab activities among groups, many of the lectures were presented after many teams had completed the relevant activity, making them effectively useless. The content in other lectures was never assessed or utilized in any way by other parts of the course, leading to low student engagement with the content.

In the revised course, lectures were only given for the first third of the semester and were limited to "critical" topics that would either be directly relevant to their lab activities (i.e., error propagation analysis, chemical process safety, instrument diagrams, communication skills, and utilizing the library resources to find technical references) or would not be covered in any of their other courses (i.e., types of flowmeters, rotameter calibration). Student feedback in 2016 indicated that the lectures could still use significant improvement, so further changes were made in 2017 to increase active engagement in some of the lecture topics (communication skills, error propagation).

METHODS

Students taking the course in the Fall 2016 and Fall 2017 semesters completed an instrument to measure engineering self-efficacy both at the beginning of the course and after the course had ended. The authors were unfortunately unable to obtain similar data for the Fall 2015 students, which could have served as a historical control group. The instrument, developed and validated by Mamaril et al.,[16] consisted of four subscales measuring students' self-efficacy regarding their general engineering capabilities, experimental skills, design skills, and tinkering ability. However, the tinkering subscale items were omitted. This was done because the unit operations course did not focus on students' ability to tinker (assemble, disassemble, or build machines) and it was thought that the course would not have much effect on students' self-efficacy in this area. Furthermore, Mamaril's validation study showed through factor analysis that each self-efficacy subscale (i.e., general, experimental skills, design skills, or tinkering) was separate from the others. Therefore, the omission of tinkering self-efficacy from the present study should not have any effect on the results. Students responded to the self-efficacy items on a 6-point Likert scale (1 = *completely uncertain*, 6 = *completely certain*).

In addition to the self-efficacy instrument, the post-course survey also included items relating to how effectively the course achieved its learning objectives as well as which parts of the course (teams, roles, open-ended problems, instructor interactions, TA interactions, pre-labs, lab reports, oral presentations, or lectures) contributed to the students' learning and why. The items about the learning objectives were on a 6-point Likert scale (1 = *strongly disagree*, 6 = *strongly agree*). For the items about contributions to learning, students were first asked how important each part of the course was for their learning (5-point Likert scale where 1 = *not at all important*, and 5 = *extremely important*). They were also asked which particular part of the course contributed most and least to their learning and why. Finally, students were asked to describe anything else they felt the researchers should know about their beliefs in their engineering skills, their achievement of course learning objectives, or the effect of the course structure on their learning.

Over both semesters, 69 out of 79 students (87.3%) consented to provide demographic information (gender, ethnicity, ACT test scores) and completed both surveys. The 2016 completion rate was 33 of 40 (82.5%), and the 2017 completion rate was 36 of 39 (92.3%). Demographic data were obtained with student consent from the office of the Registrar. Changes in the self-efficacy scores were evaluated relative to course semester, student gender, ethnicity, and ACT composite score. A total of 30 female and 39 male students were surveyed. Ethnicities were divided into three sub-categories: (1) White (any students with White as their only race, $n = 48$), (2) Asian (any students with Asian or Asian and White listed as their race(s), $n = 13$), and (3) Underrepresented Minorities (URM, any students listed as Hispanic, Native American, Black, or Pacific Islander, or any of these in addition to White, $n = 8$). ACT composite score is defined as the average of ACT English, reading, science reasoning, and math, or the total SAT score (verbal + math) converted to an ACT composite score.[18]

All statistical calculations were performed using the Statistical Toolbox in MATLAB. Comparisons between two means were performed using two-tailed paired-sample *t*-tests. For comparisons of more than two means or to test significance of external factors, ANOVA was performed followed by Tukey's Honestly Significant Difference (HSD) test. *p*-values less than 0.1 were considered weakly significant, and *p*-values less than 0.05 were considered strongly significant.

RESULTS AND DISCUSSION

Engineering Self-Efficacy

The results of the engineering self-efficacy test are shown in Table 1. When comparing mean pre-course and post-course scores, there was no significant change in any combined self-efficacy subscale (general, skills, or design). However, looking at the instrument items individually for the overall data set, six of the items showed a significant improvement:

- *I can orally communicate results of experiments (#8)*
- *I can communicate results of experiments in written form (#9)*
- *I can identify a design need (#10)*
- *I can develop design solutions (#11)*
- *I can evaluate a design (#12)*
- *I can recognize changes needed for a design solution to work (#13)*

All six of these items were either in the skills or design subscale and all related to communication or design evaluation/solutions. Most of these items showed similar improvements in both 2016 and 2017.

Regarding general self-efficacy, no significant difference was seen in any general self-efficacy items in the overall (two-year) data set or in the 2016 data set. Student comments in 2016 generally indicated that, as senior-level students, they had had several years of engineering courses with which to bolster their confidence in their classroom abilities, so general self-efficacy was not something that would have changed in that semester:

> *I've always been fairly confident in my ability to learn and do well in STEM courses, I don't think the way this course was run affected my belief in my skills in either a positive or negative way.*

However, looking at the 2017 data set, the 2017 students exhibited a significant drop in four out of five general self-efficacy item scores. Looking at open-ended student comments, there is some evidence that these decreases in self-efficacy may be largely related to other courses in the curriculum, some of which are already targeted for curricular improvements. For example:

> *I think the unit ops course was good at reinforcing skills I already had, and also made me aware of skills I still need to develop (like error and statistical analysis of data).... My belief in my engineering skills in general has probably gone down over the course of this semester. This is because I have not been able to master the topics in my other chemical engineering classes (not unit ops)... I am now starkly aware of all the skills and knowledge that I should have acquired but didn't, which is quite confidence reducing.*

TABLE 1
Improvements in student Engineering Self-Efficacy. $n = 69$, ** $p < 0.05$ and * $p < 0.1$.

Item #	Self-Efficacy Subscale	Item Text	Difference in Mean Response (Post - Pre)		
			Overall	*2016*	*2017*
1	General	I can master the content in the engineering-related courses I am taking this semester.	-0.23	0.15	-0.58**
2	General	I can master the content in even the most challenging engineering course if I try.	-0.01	0.27	-0.28
3	General	I can do a good job on almost all my engineering coursework if I do not give up.	-0.25	0.18	-0.64**
4	General	I can learn the content taught in my engineering-related courses.	-0.19	0.12	-0.47**
5	General	I can earn a good grade in my engineering-related courses.	-0.14	0.06	-0.33*
6	Skills	I can perform experiments independently.	0.07	0.03	0.11
7	Skills	I can analyze data resulting from experiments.	0.16	0.15	0.17
8	Skills	I can orally communicate results of experiments.	0.30*	0.39**	0.22
9	Skills	I can communicate results of experiments in written form.	0.49**	0.58**	0.42**
10	Design	I can identify a design need.	0.36**	0.33**	0.39*
11	Design	I can develop design solutions.	0.35**	0.39**	0.31
12	Design	I can evaluate a design.	0.40**	0.39**	0.42**
13	Design	I can recognize changes needed for a design solution to work.	0.32*	0.39*	0.25

Regarding the other subscales, improvements were generally seen in design self-efficacy scores ("Design" subscale). The authors found this somewhat surprising, since the students had had very little instruction in design up to that point in the curriculum, and indeed would not be taking the senior design course until the following semester. Perhaps the improvements in these self-efficacy scores might be related to the emphasis on designing experiments and data analysis to achieve the semi-ambiguous goals of the lab. Another unexpected result was that students did not show improvements in their self-efficacy relating to experimental design or analysis (items 6-7), which is somewhat surprising since these skills were a focus of the revised unit operations course. This lack of improvement could also be due to the fact that the students are highly experienced seniors, the majority of whom have been engaged in research and other lab experiences during their tenure as undergraduate students.

In analyzing the results for each self-efficacy item, the authors were additionally interested in seeing if there was any effect from outside factors, such as gender, ethnicity, or college preparation. Historically, science, technology, engineering and math (STEM) fields have exhibited a "leaky pipeline" with regards to women and minorities.[19] These students often leave STEM due to, e.g., a lack of support structures, stereotype threat, and cultural isolation,[20] so it seems reasonable that lower self-efficacy could also contribute to the "loss" of students in STEM. Other studies suggest that active learning methods (such as those employed in this study) are especially beneficial for women and minorities.[21-22] Together, these ideas indicate that gender and ethnicity could be important factors. In addition to gender and ethnicity, the authors also looked at the potential effect of ACT scores, a measure commonly used to indicate the level of college preparation. It could be argued logically that students who come to college more prepared (as evidenced by a higher ACT score) could have higher engineering self-efficacy. Thus, the authors were primarily interested in controlling for this outside factor (i.e., to see if changes in self-efficacy persisted even when the effect of ACT score was removed).

To assess the effect of gender, ethnicity, ACT composite score, and course year, a four-way ANOVA was performed on the differences in item scores. No items were significant with relation to gender. This lack of overall difference matches with Mamaril's results, in which there was no significant distinction in engineering self-efficacy between men and women.[16] With respect to course year, a single item (#1, "I can master the content in the engineering courses I am taking this semester") was weakly significant, which matches the results for general self-efficacy discussed above. Two items (#6, "I can perform experiments independently" and #12, "I can evaluate a design") were weakly significant with relation to ACT score.

With regards to ethnicity, three items in the four-way ANOVA were strongly significant: #1 ("I can master the content in the engineering courses I am taking this semester"), #4 ("I can learn the content taught in my engineering-related courses"), and #5 ("I can earn a good grade in my engineering-related courses"). Additionally, one item was weakly significant (#3, "I can do a good job on almost all my engineering coursework if I do not give up"). The mean difference in the item scores were more closely assessed using Tukey's HSD test. For the items showing a strongly significant effect (#1, 4, and 5), Asian students exhibited a significantly lower ($p < 0.05$) mean difference as compared to White students. No other comparisons were significant. Given the small sample size of Asian students ($n = 13$), it is possible that a few students in the sample are skewing the results. It is also difficult to draw reliable conclusions from an analysis with this small sample size; however, previous studies have also suggested that Asian STEM students may have lower academic and general self-efficacy compared to other ethnic groups.[23-24]

Overall, the self-efficacy scores demonstrate that students showed an improvement in their beliefs about their engineering communication and design skills, but that these improvements were not necessarily linked to gender or ACT scores. The improvement of self-efficacy in communication skills (items 8-9) might have been expected from the strong emphasis on writing and presentation skills in the course. Similarly, improvements in design self-efficacy may be related to the students' perception of improved skills in design of experiments. Some general engineering self-efficacy items showed a drop in score that may be related to ethnicity or other departmental courses. Over the course of two years, it can be seen that students' self-efficacy improved over the semester in which they took the unit operations laboratory course, and the aspects that did improve are likely related to the revised course format, which emphasized communication and experimental design skills.

Achievement of Course Learning Objectives

As part of the post-course survey, students were asked about how well they perceived the course to have achieved its learning objectives. The results from both course years are shown in Table 2. The items were structured with a 6-point Likert scale in which "1" indicates strong disagreement that the learning objectives were achieved, and "6" indicates strong agreement that the learning objectives were achieved. For every single learning objective, the median score was equal to 4 ("somewhat agree") or 5 ("agree") and the average score was above 4.3, indicating that the students felt that the course achieved its objectives. Furthermore, the scores for each objective in 2016 were extremely similar to those in 2017; even the relative differences between each objective were approximately the same from year to year.

The highest-scoring item concerned learning how to use chemical engineering theories and principles for the analysis of unit operations (score = 4.90). This result might have been expected since the focus of the course experiments was to apply theory to the analysis of chemical engineering equipment. The next-highest-scoring item (score = 4.67) concerns the students' understanding of how chemical engineering processes are useful in chemical engineering-related industries. Although this concept was not necessarily a focus of the course, all of the lab experiments were set in the context of a "real-world" situation, which could have contributed to the successful achievement of this learning objective.

TABLE 2
Student's perception of their achievement of course learning objectives. Responses were given on a 6-point Likert scale (1 = *strongly disagree*, 6 = *strongly agree*). SD = standard deviation, $n = 69$.

Learning Objective	Median	Mean	SD
This course helped me understand general theories and principles important to chemical engineering.	5	4.65	1.32
This course helped me see how to use chemical engineering theories and principles for the analysis of chemical engineering unit operations.	5	4.90	1.35
This course taught me to apply effective experimentation techniques.	5	4.43	1.39
This course taught me to apply effective safety procedures.	5	4.33	1.40
This course helped me understand how chemical engineering processes and unit operations are useful in chemical engineering-related industries.	5	4.67	1.46
This course improved my ability to write reports that effectively summarize experimental procedures, observations, results, and conclusions.	5	4.61	1.44
This course improved my ability to present reports that effectively summarize experimental procedures, observations, results, and conclusions.	5	4.52	1.43
This course improved my ability to work in a group.	4	4.45	1.41

The lowest-scoring items were associated with the application of effective experimentation techniques (score = 4.43) and safety procedures (score = 4.33). While the students on average felt that these objectives were achieved, these lower scores perhaps indicate areas for improvement. As part of the course, the students were expected to research and develop effective experimental techniques and safety procedures, but these concepts were not explicitly taught, possibly resulting in lower achievement scores for the related learning objectives.

Contributions of Course Components to Learning

Because many changes were made to the course structure and implementation, it was essential to determine which component(s) were critical for student learning. First, students were asked to rate the importance of each component on a scale from 1 (not at all important) to 5 (extremely important). Aggregate results from both course years are shown in Figure 2. Next, students were asked to choose the component that contributed the most to their learning and the component that contributed the least to their learning. The aggregated 2016-2017 results are shown in Figure 3.

In the data aggregated from 2016-2017, the least valuable course component (Figure 2) was clearly the course lectures, which had a statistically lower rating than any other component ($p < 0.01$ for all comparisons performed with Tukey's HSD) and were also chosen by a majority of students to be the least important for their learning (Figure 3). This result is likely due to the style of the lectures, which were largely topic summaries. In the words of one student:

> *The lectures were surface-level and did not go in depth into the material at all. They felt more like a commentary/summary of different subjects, rather than a teaching/learning environment.*

Out of the remaining components, TA interaction and feedback was the only other item with an average score indicating unimportance (2.71). This result is actually as expected, as the primary job of the TAs was to make sure the students maintained safe conduct in the lab. Further, the TAs were told not to give students the answers to their questions if those questions were related to achieving the lab goals, as the instructors wanted the students to learn to find the information on their own. Thus, the TAs often did not interact much with the teams or provide direct feedback on the teams' work.

On a more positive note, the remaining components of the course were all rated on average to be at least slightly important for learning. In particular, the following factors were chosen by at least 10% of students to be the most important: lab reports, working in teams, open-ended nature of problems, and defined roles for teams. These choices were explained by some of the students as follows [emphasis added]:

> *The* ***lab reports*** *required us to deeply examine all of our data and come up with an explanation for it in a clear and concise way. After they were done, all of the concepts of the lab really came together and were solidified in our minds.*

> ***Working with other people*** *forced me to meet deadlines because it wasn't just my grade at stake. I also had to be prepared to justify my ideas to my teammates. I also learned from my teammates when I had trouble understanding concepts and my teammates clarified it for me.*

> *Knowing* ***certain roles*** *left little room for uncertainty. Each member had her own assigned duties for the lab and it made the process of designing and running the*

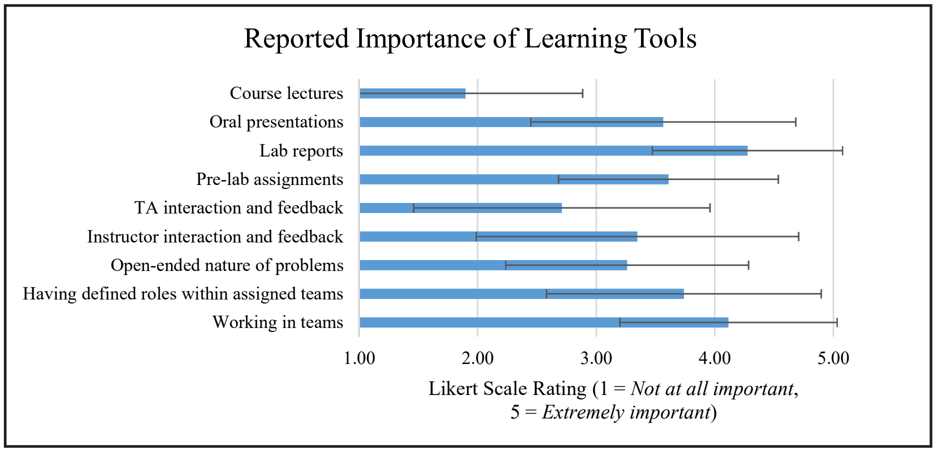

Figure 2. *Students' perceptions of the relative importance of course components for their learning. Bars indicate mean response, and error bars indicate one standard deviation (*n *= 69).*

experiment from start to end much easier.

The nature of ***not initially knowing exactly what to do*** *in lab forced a lot of outside research, and a deeper understanding of the topic at hand. I feel like I gained a lot from this sort of investigative engineering structure of lab than I had in any labs in the past.*

Interestingly, the relative choices of most and least important factor between 2016 and 2017 exposed several distinctive differences between the course years (Figure 4). Perhaps the most striking difference is the reduction in the number of students choosing lectures as the least important course component. Because the 2016 results had been so negative with respect to the lectures, the lecture schedule was further refined in 2017 to increase active learning and engagement over critical topics (such as communication skills and error propagation), and to reduce coverage of topics that would not be critical to the course (for example, discussion of equipment not seen in the lab). Although lectures were still largely thought of as unimportant for learning in 2017, a much smaller percentage of students chose that component, so it is possible that the changes to the lectures between 2016 and 2017 improved their value. It is clear, however, that they could be improved further.

Another major difference between 2016 and 2017 is the increase in proportion of students finding TA interaction to be least important. As discussed previously, the TA role was not designed to be particularly "useful" to the students. An additional factor in 2017 was that the TAs were not assigned until very close to the start of the semester, so there was not as much time for TA training as might be desired. With further TA preparation, future students may find them more helpful.

In terms of most important course components, the 2017 students also held different opinions from those in 2016. The largest changes were with regards to lab reports (decrease from 2016 to 2017), open-ended nature of problems (increase), and having defined roles (increase). Frankly, the authors felt that the 2016 students underestimated the usefulness of the open-ended nature of the problems as well as team roles, and were happy to see more students appreciating these aspects of the experience. Anecdotally, the instructor noted that in the old version of the course, students rarely discussed any of the chemical engineering principles with each other. Instead, they would hurry to get through the lab instructions and get the required data as quickly as possible, never stopping to reflect on how their actions related to the theory behind the unit operation. In the revised version of the course, student groups would often have detailed discussions on how the equipment operation related to particular theoretical results, or about what a certain result might mean, or how they might achieve a certain result through the manipulation of the equipment. Teams did not rush through the labs to try and "check the boxes" – they wanted to make sure they were obtaining the correct data. In short, every student appeared to spend significantly more time (1) thinking about the principles of chemical engineering unit operations and (2) reflecting on how his/her procedures related to his/her data. In the words of one student,

By working in teams, we were able to really discuss what the lab situation is and why we concluded what we did. We would fill in gaps in each other's knowledge and

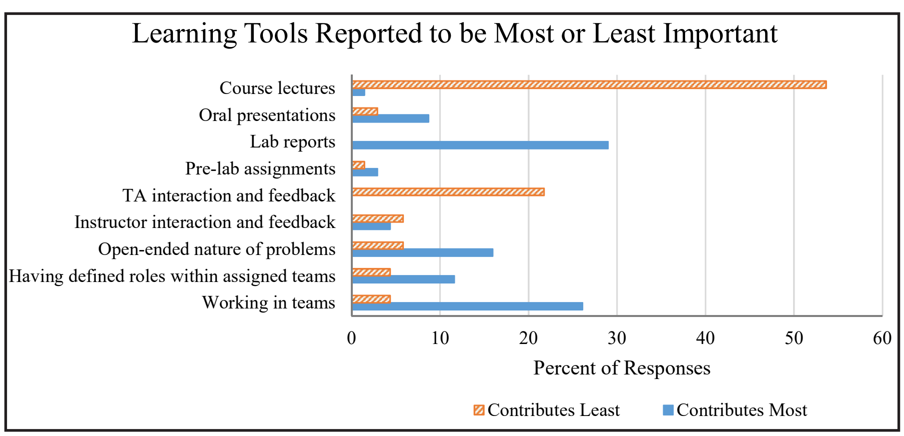

Figure 3. *Students' choices for the most and least important course component for their learning. Bars indicate percentage of students choosing that response (*n *= 69).*

challenge each other's ideas. It was a great way to solidify our foundation knowledge of chemical engineering concepts.

In terms of the importance of lab reports, even though the proportion of students choosing them to be the most important dropped between 2016 and 2017, nearly 20% of students in 2017 still felt them to be critical. As expressed by one 2017 student,

The lab reports required students to communicate the meaning of the data in a relatively simple, written way, which helps translate the unit operation into terms that I'll remember for a long time.

These data and representative comments demonstrate that several of the modifications to the course were critical to its success with regards to learning, although opinions on what was most/least important somewhat differed from year to year. In particular, requiring the students to write full lab reports on their topics (as opposed to filling in a worksheet) seems to have been quite helpful to the synthesis of knowledge. It is also encouraging to see that the open-ended nature of problems was also chosen by numerous students to be the most important factor for learning, as this change was central to the redesign of the course. Likewise, teamwork and defined roles played a large role in learning, as might be expected.

Overall Course: Achievement of Goals, Improvements in 2017

From the above data, it is clear that several components of the modified unit operations course contributed strongly to student learning and growth in the area of engineering skills and design. In particular, requiring a formal report of their findings was reported by the students to result in strong internalization of course concepts and content.

Students did not always enjoy the open-ended format of the activities, but many considered it effective or useful, especially because it was intended to be closer to a "real-life situation" than most courses. As one student noted,

Looking back over this course, I remember something a trainer had yelled out at our group while doing a body hardening session. It was a bit too colorful for this survey, but the gist was that he'd be damned if the first time we took a punch was in a real fight, so we weren't supposed to pull punches or kicks. This class was a bit like that. The first time we're asked to characterize a distillation column with incredibly vague instructions and expectations shouldn't be in at our first job, but at school. That way, we'll get a poor grade and guidance on how to improve rather than unemployment.

Another student also remarked on the connections between the open-ended format and success in the "real world":

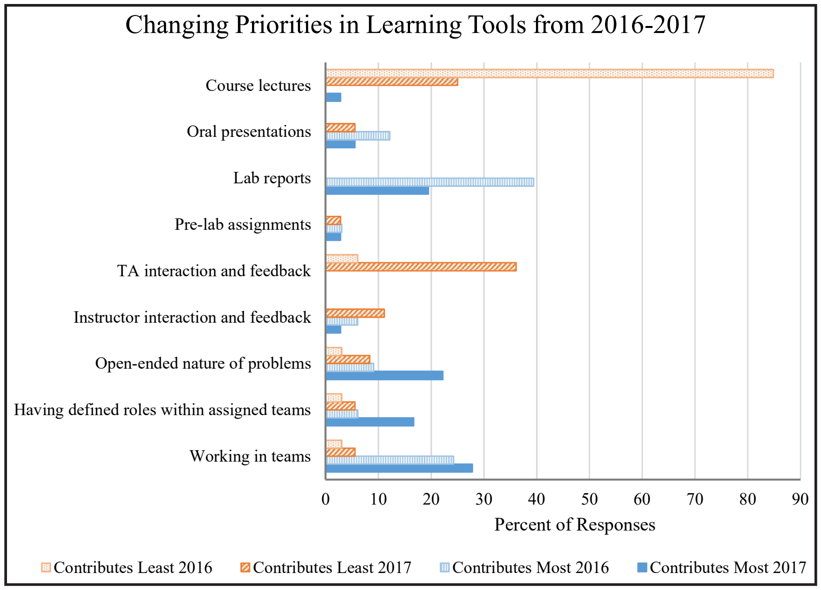

Figure 4. *Students' perceptions of the most and least important course components showed significant change between 2016 and 2017. Bars indicate percentage of students choosing that response* (n_{2016} *= 33,* n_{2017} *= 36).*

This class was really great at building engineering skills. It was also a fantastic point to use in interviews, because we worked in teams, we built reports on results and presented. All things employers want to hear about. [...] The open ended structure to this course was challenging at first. But once we got a hang for how things worked, it no longer was an issue. The open-ended structure definitely prevented just following a manual of instructions which absolutely encouraged us to think more about the task and to draw upon background knowledge.

In addition to improvements in the lectures, other feedback was also used to improve the course between 2016 and 2017. For example, several students noted that the 2016 rubrics often did not scale properly or were too ambiguous, so the language was redrafted to increase clarity and fairness. Similarly, some of the students desired improvement in the area of instructor feedback to students. One student in 2016 made the following comment:

While I like how we were given a lot of time for each lab, the overall structure didn't help us truly learn the theory behind each unit operation. It was hard to know if you were doing anything right because there was a lack of verification.

Although the instructors would spend time in the lab each week with each team, the teams in 2016 did not experience any formal feedback until the time of the oral presentations and report grading. This practice resulted in a lot of student uncertainty and frustration. Therefore, in 2017, the instructors instituted a "mid-unit" assignment in which the students were required to lay out their experimental plan for the next two weeks of lab, as well as describe in detail how some of their instruments took measurements (this was noted by the instructors to be a weakness in 2016 that resulted in major misunderstandings of student data). The mid-unit assignment allowed the instructors to see more clearly where student teams might be getting "off-track", and this likely helped prevent several experimental design catastrophes. Overall, there were far fewer comments regarding these aspects of the course in 2017, potentially indicating that the changes made were at least somewhat effective in addressing these shortcomings. Given that there were some difficulties providing feedback to students, exploration of additional methods of feedback for future iterations of the course may be useful. For example, previous research has suggested peer feedback and self-reflection can be useful tools in a unit operations course.[5]

CONCLUSIONS AND FUTURE WORK

The revision of a unit operations laboratory course to be more open-ended and focus on technical communication resulted in many positive outcomes: increased student self-efficacy in the areas of communication skills and design, achievement of course learning objectives, and increased in-lab student engagement. With regards to self-efficacy improvements, there was no perceived effect of gender or ACT score, although there were minor differences for Asian students relative to White students. Overall, however, the results indicate that students generally benefited from the revised course experience. From student reporting, lectures and TAs were the least useful component of the course, while lab reports, teamwork, and open-ended problem-solving contributed the most to their learning. Future versions of the course will focus on improving TA training and interaction, timely grading, quality/usefulness of lectures, and/or potentially the addition of additional student reflection exercises. Future studies could also examine the effects of these improvements.

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