Appendix III

Unit Operations Laboratory
Articles
2019 Summer II Unit Operations Laboratory Students and Faculty
Enhanced Experiential Learning in the Unit Operations Laboratory

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Abstract

In most Chemical Engineering departments, the Unit Operations Laboratory is used to deliver hands-on experience with experimental equipment to students that have completed junior-level transport phenomena lecture courses (Fluid Mechanics, Heat Transfer, and Mass Transfer). At the Colorado School of Mines, this laboratory is delivered as an intensive six-week summer course. Students work in teams on a variety of experiments that illustrate principles in fluidic, thermal, and chemical systems. Students engage in two eight-hour laboratory work days each week. The course is designed to deliver experiential learning; students generate an experimental design to achieve broad-based objectives, and perform extended experimental work with long laboratory times. The active phase of learning that is naturally present in laboratory work is enhanced by providing latitude to the students in their experimental plans, and by allowing them to reflect on their lab experiences when repeating an early experiment at the end of the Session.

Keywords

Experiential learning, unit operations laboratory.

1. Introduction

The curricula of most Chemical Engineering departments in the United States include the Unit Operations Laboratory, an experimental laboratory focused on the application of typically junior-level courses such as thermodynamics, fluid mechanics, heat and mass transfer, and separations. Traditionally, this laboratory is offered during the junior (3rd) year at institutions offering 4-year degrees, and is usually organized over the course of two semesters or two quarters. The relatively late positioning of the laboratory among the typical required courses for the Chemical Engineering degree makes it a good candidate as a capstone course\textsuperscript{1}; students may practice open-ended experimental design\textsuperscript{2,3} and use their experimental work to perform detailed data analysis, to develop professional-grade thinking and reporting skills\textsuperscript{4,5}, and to demonstrate the ability to work on task-oriented teams under defined time constraints.

In the Department of Chemical and Biological Engineering at the Colorado School of Mines (CSM), the Unit Operations Laboratory is offered between the Fall and Spring semesters; students enroll in one of two six-week summer “field sessions,” each session providing laboratory resources and instruction for between 70 and 80 students working in teams of three. Students work in the laboratory twice weekly (either on Monday/Wednesday or Tuesday/Thursday splits) for eight-hour shifts, with different laboratory experiments performed during any given week. The laboratory experience is designed to build and enrich each student’s higher-order thinking skills and professional practice awareness. An emphasis is placed on experimental design, the collection and interpretation of data, and communication of
conclusive results in oral and written formats. Since the lab’s general format was adopted in the mid-1980s, instructors have provided particular attention to the careful examination of student thinking as an aid to teaching - including the use of Socratic questioning techniques at various phases of the laboratory sequence. The coaching role of the instructors allows them to oversee the student learning process – one that is based on a cycle of improving understanding through each student’s process of design, lab performance, data analysis, and their own appraisal of work done in the laboratory. Each student gains experience in all stages involved: pre-lab planning, execution of the plan in the laboratory, calculation and presentation of the main results, and evaluation of the quality of the data and the lab procedure that was originally selected. As a “final exam” of sorts, students perform their last assigned laboratory experiment by repeating an early experiment (with the same team members) by creating new experimental objectives based on previous experience with the lab module.

2. Experiential Learning Model

In this section, the experiential learning techniques used in the Unit Operations Laboratory at CSM are described. The experiential learning instruction style that is put into practice in the course is based on the four-step cyclical model described by Kolb⁶. The four stages of learning, shown from a student’s perspective and in relation to a typical thinking taxonomy, are illustrated in Figure 1.

![Image of experiential learning cycle and hierarchical thinking taxonomy]

When a student group begins preparation for a new experiment, they bring the factual recall and comprehension gained from the prerequisite lecture courses (gray on the taxonomy diagram). Lab preparation begins with the initial experimental design; the practical equivalent to “Synthesis” at the top of the pyramid. Putting that design into practice in the laboratory (executing the plan) initiates the learning cycle. The movement from lower-order to higher-order thinking (upward in Fig. 1b) is usually discussed as a one-way progression as the learner achieves greater mastery of a subject or technique. However, the new approaches created at the level of Synthesis may themselves be used (Application) to obtain new results that may be determined (Organization) and evaluated for quality (Judgment). This cycle may be continued as long as there are new ideas synthesized for testing.
2.1 Composition: Experimental Design (Synthesis)

At the laboratory orientation session, students are presented with a detailed schedule of which experiments they will be assigned, which members of the class will comprise each team on each lab day, and when students will be designated as group leaders - each student serving as a group leader three times over the course of the summer. Recent enrollments have involved 36 students working in the lab on a given day, with twelve distinct experiments operating with 3-person teams. Before the laboratory work day, each student team familiarizes themselves with the experimental hardware and safety guidelines provided by faculty supervisors. The team meets to select measurement and modeling techniques, and to develop a complete experimental design. This design includes a listing of detailed experimental objectives, a strategy for data collection, and a selection of statistical analyses to be applied to the experimental data. Very brief written guidelines (including safety) for each experiment are available for reference, and faculty supervisors are available to coach or mentor the teams regarding questions that arise during their design development. Before entering the lab on the experimental work day, each student team takes part in a “prelab” report session with the faculty supervisor assigned to the experiment. The supervisor examines the team’s preparation for the laboratory by investigating all aspects of the experiment: theory, system operations, personnel assignments, safety concerns, working equations and correlations, data acquisition, handling of measurement uncertainty, data analysis, and evaluation of experimental objectives. While all group members participate to some degree, the supervisor primarily interacts with the designated team leader, and the prelab grade is assigned to that individual.

2.2 Experience: Hands-on Operation (Application)

Upon completion of the prelab report, the student team commences its laboratory work, operating without input from faculty or teaching assistants (potential safety issues excepted). Student teams, as directed by their team leader, are in complete control of the execution of their experimental plans. Whereas a typical laboratory courses scheduled during a Fall or Spring semester may be limited to three or four contact hours per week, the summer setting allows students to spend up to eight uninterrupted hours gathering experimental data. This has enabled CSM faculty to employ larger experimental modules than those found in most university labs – much closer to pilot-scale than the bench-top units available commercially. Table 1 shows the various laboratory experiments available as of the 2016 Summer Field Session.

<table>
<thead>
<tr>
<th>Fluid Mechanics</th>
<th>Heat Transfer</th>
<th>Mass Transfer</th>
<th>Coupled Transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction Factor in Pipes</td>
<td>Condensing Steam</td>
<td>Staged Distillation Column</td>
<td>Liquid/Gas Absorption</td>
</tr>
<tr>
<td>Compressible Flow</td>
<td>Shell &amp; Tube Heat Exchangers</td>
<td>Packed-column Distillation</td>
<td>Drying of Solids</td>
</tr>
<tr>
<td>Pumping Power and Efficiency</td>
<td>Transient Tank Heating</td>
<td>Liquid/Liquid Absorber</td>
<td>Evaporative Cooler</td>
</tr>
<tr>
<td>Drag Coefficients</td>
<td>Brazed Plate Heat Exchangers</td>
<td>Membrane Air Separation</td>
<td>Fixed-bed Adsorption</td>
</tr>
<tr>
<td>Minor Fitting Losses</td>
<td>Forced Air Cooling</td>
<td>Pressure Swing Adsorption</td>
<td>Heat Transfer in Fluidized Beds</td>
</tr>
</tbody>
</table>

Table 1: Chemical Engineering Unit Operations Laboratory Experiments at CSM
In order to provide a foundation from which students may develop their experimental goals, some very basic (minimum) objectives are provided with the guidelines mentioned previously. For example, the Condensing Steam experiment uses double-pipe heat exchangers, internally cooled by water or ethylene glycol, with steam condensing on the outer surface of the cooled pipe. By variation of coolant flow, steam pressure, and exchanger size, the students are to use measured temperatures and flow/condensate rates to determine overall and individual heat transfer coefficients. These heat transfer coefficients are compared to predicted values from literature correlations, and dominant individual heat transfer coefficients are identified.

Certain experiments require students to perform hazard and operability (HAZOP) safety studies as part of experimental reporting, and course faculty provide a HAZOP workshop for students immediately after the initial orientation meeting. With the present scheduling strategy, each student performs at least two HAZOP analyses during the session.

The experiments are either built from the ground up by CSM laboratory personnel, or are heavily modified from stock manufacturer specifications. They are designed with flexibility in mind – such that they may be used in a variety of ways by the students according to their experimental design. For example, the pumps integrated into the Pumping Power and Efficiency experiment may be run individually, in series, or in parallel to provide a variety of options to students investigating a wide range of system power/flow operating conditions. At the end of the summer sessions, detailed feedback is requested from the students regarding how the experiments might be improved in terms of allowing new types of data to be acquired, or different analysis paths to be followed. Typical examples of these improvements include the addition of system monitoring hardware, the incorporation of automated data acquisition, or the redesign of fluid pathways.

2.3 Reflection: Determination and Communication of Results (Organization)

Upon leaving the laboratory, the team processes and analyzes the data, comparing results with appropriate theoretical models or empirical correlations. Statistical uncertainty analysis is stressed from the very beginning of the course. Two statistics workshops, which focus specifically of the handling of experimental error and the uncertainty in comparing model predictions with data, are offered in the opening weeks of the course. A statistics homework assignment and exam allows instructors to gauge the competency of the students in these operations, and the error handling approach by the team is scrutinized in detail for each report.

Data reporting is required in the form of oral and written reports, completed in an alternating sequence. For oral reports, each team is required to prepare and deliver a twenty minute presentation describing their laboratory planning, experience, and results on the day following the laboratory work day. Students are expected to participate equally in oral report delivery, both in presentation of the team’s work and in answering questions from the audience (one or more instructors and at least one other student team). Draft written reports are submitted five calendar days, including a weekend, after the experiment is completed. The draft versions of the written reports are reviewed by both the experimental supervisor and a technical communication specialist. Draft review meetings with individual student teams provide feedback and suggested corrections to writing quality and technical content before a final version of the report is submitted by the team. Oral presentations are attended by other students in the course, and by one or more faculty supervisors. Students present four oral reports, and submit four written reports on experiments completed during the course. The final report (from a repeated experiment, as detailed above) is presented as an oral briefing with handouts designed by the students.
Successful reporting requires that the team carries out detailed calculations and uses measurements and calculated quantities in comparison with theoretical relations or empirical correlations of engineering parameters (e.g., mass transfer coefficients). Communication of the team’s findings requires clear figures and tables for displaying results, as well as calculation of error propagation and related statistical analyses. More critically, each team is required to provide logical explanations for any deviations of their results from expected values, and to develop conclusions based on their overall evaluation of the work.

2.4 Conceptualization: Objective Evaluation for Redesign (Judgment)

In oral and written reports, the student teams must draw conclusions from their results that relate to any discrepancies between observed and expected outcomes. Experiment supervisors deliberately continue the use of Socratic questioning in their communications with students in order to uncover evidence of higher-level reasoning: convergent, divergent, and (ultimately) evaluative thinking. These stages of experiential learning, while rare in engineering education, are the primary goal of the laboratory’s pedagogical structure.

Helping students to progress beyond the simple reporting of experimental results without significant analysis or reflection on the data is a complicated task for the course faculty. Reports developed early in the field session indicate that students are more concerned with finishing calculations than generating meaningful results that could have an impact beyond their laboratory experience. There is indeed a reluctance among the students to make conclusive statements; many students feel an insecurity with the requirement to take a definitive stand on the results of their calculations, likely resulting from a fear of having missed an important piece of information that would have led to a different (perhaps correct) conclusion. Students that have yet to move on from simple analysis (convergent thinking) to open-ended reasoning (divergent thinking) often provide tentative implications of trends that are clear to the trained eye, yet which are not easily explained without a mastery of the physiochemical phenomena of the system. Helping students to take active steps to evaluate laboratory results critically and to make conclusive judgments about their analyses is a task best addressed by repeatedly coaching the students to adopt such a mindset.

In the late stages of the field session, as students begin their final series of experimental reports, they exhibit an increased proficiency for applying knowledge that they have learned in core chemical engineering courses (thermodynamics, heat and mass transfer, fluid mechanics) to their experimental systems. Additionally, the stated conclusions become specific and focused on understanding; students communicate what they believe that the data truly mean. They begin to indicate that they understand the limitations behind textbook equations and correlations that were once taken as Gospel.

This last evaluation of the body of work generated by the students allows them to improve their next experimental design and laboratory performance, beginning the experiential cycle anew. The cycle must always begin with an experimental design, without which any experimental work would be largely unfocused. The experiential learning cycle is repeated directly for each student when the final experiment of the session is repeated. However, it is worth noting that the lessons learned by each student enable the cycle to be repeated in principle even across different experiments – for example, evaluation of results from one experiment may lead the students to make more informed decisions about time management in the laboratory, or to try new methods for error analysis.
3. Student Course Evaluations

Detailed course and faculty evaluation forms are provided to the students at the end of every summer field session. The evaluations are completed during a course check-out meeting which involves a final concepts exam, final peer evaluations, “best teammate” awards, and return of the students’ laboratory notebooks for archiving. As a result, a 100% response rate is the most common. Data from these evaluations that relate to student assessment of higher-order thinking skills are shown in Table 2. The data appearing here spans the author’s time as an instructor for all summer field sessions from May 2012–August 2015. The total number of responses included is 434.

Table 2: Student Responses to Selected Course Evaluation Questions (2012 – 2015).

<table>
<thead>
<tr>
<th>The Instructors Helped:</th>
<th>Disagree or Strongly Disagree</th>
<th>Neutral</th>
<th>Agree or Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Me to improve my knowledge</td>
<td>4%</td>
<td>9%</td>
<td>87%</td>
</tr>
<tr>
<td>Me to develop my communication skills</td>
<td>7%</td>
<td>3%</td>
<td>90%</td>
</tr>
<tr>
<td>By providing clear and useful feedback on oral/written reports</td>
<td>11%</td>
<td>15%</td>
<td>74%</td>
</tr>
<tr>
<td>Me to understand the experiments and overall course material</td>
<td>2%</td>
<td>7%</td>
<td>91%</td>
</tr>
<tr>
<td>Me to develop my “higher-order thinking” skills</td>
<td>3%</td>
<td>4%</td>
<td>93%</td>
</tr>
</tbody>
</table>

Clearly, there is overwhelming support for the instructional methods employed in this course, as well as the active-learning nature of the work itself. Comments on the course evaluations indicate that students appreciate having the freedom to make decisions about the work that they perform, and also value the fact that they were able to take ownership of the ways in which data was analyzed and reported. Some selections from among the comments of one recent field session (2014) follow:

• “This was the hardest work I’ve ever done, but very satisfying to know that I can prove myself under difficult time constraints.”
• “Having completed field session, we as a class will have a lot of advantages versus people from other colleges that don’t have the same experience.”
• “This was a valuable class in that it showed me what I am capable of accomplishing.”
• “I would never want to go through this class again. That said, I know I will be a better practicing chemical engineer with this ‘boot camp’ on my résumé.”
• “I learned more in this course than from my other ChE courses combined. It was intense – but the workload became easier as I realized the quality of work my teams did.”
4. Feedback from Alumni and Recruiters

Alumni from the Chemical and Biological Engineering Department at CSM have long indicated that the Unit Operations Laboratory was invaluable, with many indicating that it was the most important course in terms of preparing them for an industrial or consulting job. Annual alumni surveys include the question (which does not specifically mention the Unit Operations Laboratory): “Which aspects of your education at CSM were most valuable to you in your current career?” Selected responses from the 2010 survey appear below.

• “Without a doubt, the Unit Ops lab. The ability to write a report that doesn’t need extensive editing or give a talk that doesn’t embarrass my boss goes a long way towards building job security.”
• “Unit Operations was the best preparation I received at CSM due to its hands-on application of industry equipment as well as developing presentation skills.”
• “Professors could relate class material to real world experience. Field session was a great class which gave me a dose of what to expect as a professional in the field, presentation, and thinking about exactly what it is that we are doing.”
• “It pains me to say this, but the Unit Ops lab gave a great model of a real world working situation – fast paced, heavy loads, and a focus on professional communication.”
• “My job is very similar to the way field session was run. The teamwork aspect was maybe the most valuable learning experience to me – I need those skills daily.”

The Department’s Industrial Advisory Council, which includes company recruiters that are not CSM alumni, has been very supportive (in communication, as well as through donations) of the methods and learning objectives delivered in the Unit Operations Laboratory. Some representative feedback from the Council and other campus recruiters appears below.

• “We find ourselves hiring 2 or 3 Mines ChE grads each year, though we recruit in multiple states. The Mines grads hit the ground running, head and shoulders above other new hires in terms of presentation skills and critical thinking.” (Schlumberger)
• “I trust the new grads from Mines to handle problems that aren’t completely defined yet – they don’t mind diving right in and finding out what needs to be done.” (Baker Hughes)
• “We hire a lot of Mines kids, and they know how to work. I don’t need to tell supervisors to watch their progress marks every month, and they don’t waste anyone’s time.” (Ball Aerospace)
• “Our experience with CSM chemical engineers has been fairly limited, but very positive. They come in as top communicators, and are known to be problem solvers.” (Honeywell)

5. Conclusions and Recommendations

The Chemical Engineering Unit Operations Laboratory, in its present format, is the product of nearly thirty years of pedagogical focus on building our students’ abilities of learning by doing, communication, design, and open-ended problem solving skills. Faculty best accomplish these goals not by lecturing or posturing as authority figures, but rather by coaching and probing the thought processes of students as they work to define experimental goals and describe the outcomes. We see a great improvement in these skills throughout the course of each field session. Although the workload is high and time constraints are significant, the students demonstrate a greater mastery of the fundamentals of the chemical engineering discipline. The instructors of our laboratory have provided the following recommendations to educators interested in using their own laboratory courses to enhance student performance through experiential learning:
• The CSM field session is a rare example of an immersive class experience, but the techniques described here should translate well to laboratory courses that operate on a traditional semester- or quarter-based schedule.

• There is no perfect way to make students into better thinkers or communicators. Rather, we have found that setting clear, high expectations for students from the start and providing the proper student/faculty interaction standards are the best ways for helping students develop these skills.

• Preparation for laboratories (initial compositional work) and placing responsibilities on students that affect the evaluation of others (team values) are crucial to initiating effective experiential learning cycles.

• The development of skills through experiential learning is often slow, and will occasionally frustrate students that are unaccustomed to the instructional style. However, if the process is applied one step at a time, faculty may successfully raise student performance, expectations, and self-confidence.

References


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Best Practices in Teaching Unit Operations: the “Field Session” Lab Experience at the Colorado School of Mines

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The results of a 2017 comprehensive survey of 70 programs [1] revealed that the unit ops laboratory course offered during a 6-week summer “Field Session” at Colorado School of Mines (CSM) is an outlier from other U.S. programs in many ways. The biggest differences between this course and the typical unit ops course run concurrently with other courses are the immersive experience and the extent and nature of the real-time formative and summative assessments provided. Students and faculty work full- or close to full-time (students ~40-60+ and faculty ~30-40+ hours per week) exclusively on this course. This level of personal interaction and feedback, and the ways in which they are conducted, build connections and community amongst all involved and motivate student engagement and cooperation. This in turn leads to students achieving significant technical and non-technical learning outcomes and the course is recognized by alumni and recruiters as highly effective at preparing students for the workplace. Furthermore, despite the intense pace and depth and breadth of skills covered and assessed in the course, the fail rate is effectively zero.

The course is offered twice each summer, each 6-week session currently accommodating up to 84 students, with a Student-to-Professor ratio of up to 12:1 (yes, 7 faculty per session!). There are also writing instructors, a lab manager, and at least two TA’s working full- to nearly full-time to help manage the course. There is 1 experiment per 6 students and each professor is in charge of 2 experiments. Each student runs 8 of the experiments and repeats the second one as their 9th with additional objectives that their group designs. During week 1 students run one and weeks 2-5 they run two experiments per week, each with different teams, delivering one oral presentation and one written report per week. Hence, students complete a total of nine summative communication reports, placing this program in the <15% category of all programs surveyed in 2017 whose students do 9 or more experiments.

In addition to running and reporting on the experiments, students attend workshops on Safety, Graphics, Statistical Analysis, Technical Writing, and Higher-Order-Thinking Skills. For three of the four written reports, students attend separate writing-focused and technical draft reviews. For both reviews the faculty members have read and commented the draft in advance. These 20-45 minutes each review sessions offer the students a plethora of useful timely feedback prior to summative assessment. This significant and coordinated time investment by both instructors and students is one of the key elements of this format that is difficult to duplicate in a more typically-timed course.

The decades-running highly effective structure and delivery method of this course will be presented along with results from course evaluations, student assessments, and alumni and recruiter surveys. Comparative assessments of a variation of the course in which it was framed in a more creative and friendly-competition-inviting manner will also be presented. Many “best practice” elements of this course will be discussed in terms of their portability to the typical semester or quarter timeframe.
Introduction

The Unit Operations laboratory course is a central part of the undergraduate Chemical Engineering curriculum, as it is most often one (or both) of only two lab courses required of all students for graduation [1-2]. While there is growing interest in using virtual laboratory experiences [3-4], the same authors who have shown evidence that these are valuable learning opportunities simultaneously advocate for continuing to use tactile, in-person laboratory experiences [5-6] whenever practicable and affordable. In addition, a comprehensive survey of seventy undergraduate Chemical Engineering programs in the U.S. in 2017 revealed that the majority of virtual labs were experiments on process control, followed by reactor experiments, with very few on the more traditional transport-related unit operation experiments in Fluids and Heat and Mass Transfer [1-2].

A comprehensive dataset of 148 undergraduate Chemical Engineering programs listed in a public directory analyzed in 2016 showed an average of 4.5 semester credits (or equivalent) of lab courses were required for graduation [2]. The Unit Operations laboratory course or “Field Session” offered exclusively during the Summer at CSM, at 6 semester credits, is an outlier from most U.S. programs in this and other metrics accounted for in a more detailed, lab-focused 2017 survey of 70 programs [1]. These survey results prompted the writing of this paper.

While many of these differences can be highlighted as great successes of this course, one of the most important aspects of Field Session could not have been captured by this survey: the student-faculty interactions promoted consistently throughout the course. From individual group pre-lab and draft report meetings to Friday whole-group debriefing meetings and combined faculty and student lunches where more informal technical and even social conversations take place, the amount and quality of student-to-faculty interactions are unparalleled. We believe these are two of the most important keys to the success of this course in terms of student learning and alumni perceptions.

Program Description

The Chemical Engineering program at CSM, is one of the twenty largest undergraduate programs in the country, graduating over 150 students per year [7]. While this might otherwise suggest a possible reason for our being an outlier in other ways in the 2017 survey, rather, programs graduating over 120 students were slightly over-represented in this later survey [1]. Despite having doubled and redoubled in enrollment multiple times since this course was first implemented at CSM, it is still centered around principles developed decades earlier for a much smaller program: the cultivation of higher-order thinking (HOT) in a fast-paced laboratory course [8-9]. In fact, the course still adheres to the same structure described in 2016 [10], only now accommodates up to 84 students per session and 14 different experiments running simultaneously. This paper focuses on comparing this course against the national survey results but will also highlight the more unique aspects of the course as well as recent developments to this course and the changes made since the previous paper was presented in 2016.

Field Session aligns with other Unit Ops courses across the country in several ways. The categories of course objectives (learning outcomes) that are represented in more than 50% of the 2017 respondents are also represented here, with the exception of “Practice engineering design” [1] (which is product-, not process-focused [11]). Students do engage in design of experiments in Field Session. Furthermore, all of the experiments in this course may be classified as Fluids-, Heat-, or Mass-related, with some experiments also emphasizing concepts of property measurement, chemical reactions, and biology or bio-engineering. Finally, safety is presented in a HAZOP module including a lecture and assignment, the two most common means of approaching safety in Chemical Engineering laboratory courses [1].
As mentioned above, the most profound way in which this course differs from the common practices amongst Chemical Engineering Unit Ops courses nationwide is that it takes place in six weeks in the summer. Each six-week session accommodates two schedule groups, currently of up to 42 students. A typical schedule for weeks 1 through 5 for a student in a “Monday/Wednesday schedule” group is provided in Table 1.

<table>
<thead>
<tr>
<th>Week</th>
<th>Due</th>
<th>Do</th>
<th>M</th>
<th>T</th>
<th>W</th>
<th>Th</th>
<th>F</th>
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<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>Orientation/Tour &amp; Safety Lectures</td>
<td>Statistics &amp; Graphics Lectures</td>
<td>Lab 1</td>
<td></td>
<td>Debrief + Writing &amp; Stats Workshops</td>
</tr>
<tr>
<td>2</td>
<td>Draft 1 Due</td>
<td>Lab 2</td>
<td>Draft Rev 1</td>
<td>Oral Report 2</td>
<td>Lab 3</td>
<td>Final Report 1 Due</td>
<td>Debrief + HOT &amp; Stats Exam</td>
</tr>
<tr>
<td>3</td>
<td>Draft 3 Due</td>
<td>Lab 4</td>
<td>Draft Rev 3</td>
<td>Oral Report 4</td>
<td>Lab 5</td>
<td>Final Report 3 Due</td>
<td>Debrief + Writing Workshop</td>
</tr>
<tr>
<td>4</td>
<td>Draft 5 Due</td>
<td>Lab 6</td>
<td>Draft Rev 5</td>
<td>Oral Report 6</td>
<td>Lab 7</td>
<td>Final Report 5 Due</td>
<td>Debrief</td>
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<td>5</td>
<td>Final Report 7 Due</td>
<td>Lab 8</td>
<td>Oral Report 8</td>
<td>Lab 9</td>
<td></td>
<td>Oral Briefing 9</td>
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</table>

Students are further divided into sub-groups or “houses”, two of which follow the Monday/Wednesday schedule and two of which follow a Tuesday/Thursday schedule in which the experiment-related activities and due dates are simply shifted later by one day. This schedule shows the quick turnaround times students must meet with their even-numbered experiments (2, 4, 6, and 8) and experiment 9, for which they give an oral presentation or oral briefing the day after they performed that experiment. It should be noted that, of the approximately nine hours the lab is available to them each lab day, the amount of time students spend performing the experiments and collecting data varies with experiment. However, it is uncommon for students to complete any experiment more than one hour early during the first week and expected only for a few select experiments in the following week. For some experiments, particularly for most of the mass transfer experiments, students rarely finish early even by the last week of the course. Some experimental setups (e.g., staged distillation on total reflux) are powered on as early as 7:00 am by the teaching assistants and the lab is shut down around 5:00 pm, at which point students may no longer access the experiments.

For experiments 1, 3, and 5, drafts of the written reports are due five days after the experiment is run (including weekend days) and students receive feedback from the writing instructor and from the supervising professor in separate meetings the day after the draft is turned in. Final drafts of those reports are then due two days later. Experiment 7 is also a written report, but without the writing and technical reviews since by then students will have already had 3 rounds of draft reviews. The timing of analyzing data and finalizing presentations and reports for past labs, preparing to run the next lab, and attending the workshops and doing the associated assignments all overlap such that students must manage their time very well to be successful. This requirement of such a high level of coordinated time management is another element of the course (along with the intense timely feedback mentioned earlier) that cannot be easily replicated when the course is offered during a normal semester or quarter timeframe.
While this schedule is intense for students, it can be just as demanding for the instructors running the course as well. Table 2 shows a sample week 2-6 schedule (excluding some more variable tasks) of the major grading responsibilities a professor supervising two different experiments.

<table>
<thead>
<tr>
<th>Week 2</th>
<th>Due Do</th>
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<tbody>
<tr>
<td></td>
<td>Final Report 1 (MW) Final Report 1 (TR)</td>
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<table>
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<tr>
<th>Week 3</th>
<th>Due Do</th>
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<td></td>
<td>Final Report 3 (MW) Final Report 3 (TR)</td>
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The tight turnaround times for written feedback that are so helpful to students are equally demanding for professors. Each lab day for both student groups (4 days per week most weeks) we have pre-lab meetings with teams of 3 students running “our” experiments. During these pre-lab meetings we make sure the students have prepared well for their lab day focusing on 1) safety, 2) the efficacy of their experimental approach (which they design based on some minimum experiment objectives, increasing in number and complexity as the weeks go on), and 3) their analysis plan. These pre-lab meetings are run in a Socratic manner where we ask questions to guide rather than giving answers. We read and provide feedback on two drafts on Monday, go over those commented drafts in meetings with students on Tuesday, then comment the Group B drafts that same day for the Wednesday draft reviews. On top of this, professors attend two oral presentations on Tuesday and two on Wednesday, providing summative assessments to students completing even numbered experiments. Professors provide feedback on drafts within 24 hours and then grade final reports within 3 days of when they are turned in. Finally, in addition to conducting one of the workshops (equally divided among professors), we must be available while our students are in the lab and we try to visit the lab at least once (if not twice) per day to assist students running the experiments and answer any questions they might have.

There are two aspects to this schedule which may not immediately appear as portable, but which are nevertheless important elements of the success of this course. Assigning a given professor the responsibility of overseeing no more than two experiments allows him or her to specialize and therefore to more deeply probe students’ understanding of key concepts in a given experiment. While this ratio of 12:1 students-to-professors may seem difficult to meet, if the course is offered over a quarter or semester time period instead the impact may be lessened as faculty could potentially have more time between assessments. On the other hand, one of the main advantages of the quick turnaround times and significant professor-student interaction is that students tend to retain more when they get timely and detailed feedback. Therefore, someone considering adapting a unit ops course to incorporate these elements during a typical quarter or semester timeframe might condense elements of the course to keep these advantages.
Alluded to briefly above, another important aspect of the schedule is the stage-gate nature of the pre-lab meetings on the mornings of experiment days, for which every student must be a “group leader” 2-3 times per session (depending on total enrollment numbers). Although not explicitly mentioned in the previous paper on this course, professors can tell a student group that has not properly prepared for the lab that they need to go study the material and retry the pre-lab before they can enter the lab. While this is only really done in practice for a small number of groups per session, and only based on the group missing crucial information (such as safety or operational/procedural information), this check helps to prevent not only safety hazards and unnecessary risks in the lab but also fruitless days of improper or unusable data collection. Furthermore, the dynamics of having a leader “drop the ball” and having a group member “pick up the slack” (or otherwise exactly the opposite and “leave them hanging”) can be a valuable learning experience for all types of students, especially when the stakes are low enough to recover with only the loss of an hour or two. This is certainly a best practice which is highly portable and should be applied to most (if not all) laboratory courses in general. Furthermore, the pre-lab meetings are often fantastic opportunities for students to learn more before they go into the lab. They are typically run by the professor asking questions; probing for conceptual and data analysis understanding in addition to making sure students will be safe and collect reasonable data. This allows for differentiated learning where more prepared students spend less time on the lower level skills such as remembering and calculating and get deeper into the higher order learning levels such as analysis and design. Pre-lab meetings, similar to draft reviews, can run 30 minutes or longer – that’s a lot of one-on-three time between professors and students where significant learning occurs!

As described previously [10], students rotate continuously through 3-person groups and only occasionally have a repeated lab partner from within their own “house”. While this can be problematic in some ways, potentially lowering average class grades leading to more harsh peer evaluations than when students choose their own groups [12]; the authors believe this method is important not only because it more accurately represents the “real-world” (in which students will not generally be able to select their own co-workers) but also because students must work with individuals with a diverse set of skills, thereby forcing them to rapidly adapt to new group dynamics. Students often succeed at this but sometimes do not; nevertheless, survey results indicate that many of them seem to take valuable lessons away from this experience.

One prominent way in which this course deviates from the national survey results, is the total number of experiments the students perform. While over half of the programs who responded (most of which offer the Unit Operations lab during a regular term instead of summer) collect a total of only five or fewer summative communication products, this summer course requires nine: four oral presentations, four written reports, and one memo combined with an oral briefing, placing us within a small minority (≤ 10%) of all programs surveyed [1]. This broad range of experiments, combined with a repeat of their second experiment but with emphasis on new, student-designed objectives and procedures, allows students to become familiar with a wider range of equipment and theories and allows students with different skill sets to shine at different moments. Furthermore, the rotating group assignment problems are ameliorated somewhat simply by increasing the number of rotations—this makes it easier to spot trends like the “albatross” (a student who consistently “weighs down” the performance of their groups) or the “keystone” (a student who takes on more than their share of the work and “pulls up” the grades of their groups).
Another way the faculty are able to keep an eye on group dynamics is through regular meetings such as the draft reviews and pre-lab meetings. As mentioned above, students meet as a group with a writing instructor as well as the supervising professor. Employing only two writing instructors to complete up to seven drafts each overnight may seem like a lot, but these instructors are able to focus only on form while the experiment professor focuses on the content. This is not to understate the responsibility and importance of the writing instructors – they are vital to the success of our Field Session! The writing instructors provide writing workshops twice each session, in addition to editing and reviewing all draft reports. Furthermore, their feedback on grammar, spelling, formatting, voice, style, etc. allow the professors to focus their feedback on experimental methods, data analysis, and higher order thinking in the reports.

Much has been published on the development of high-order-thinking skills in this course [8]–[10], and little has changed about this aspect of the course despite enrollment numbers growing significantly since this method was first applied. The professors for each experiment have increasing expectations of the students over the duration of the course—that is, a paper which earns an A for Report #1 would only receive a B or C for Report #7—and this is clearly explained to the students during the first lecture and reinforced during class meetings.

The weekly class debriefing is another highly portable best practice. Every Friday in Field Session, all students meet in one classroom for a general meeting where the faculty and staff make any announcements to the entire class at once. Also, students are encouraged to make any course relevant announcements they’d like to make. This has proven to be highly valuable for maintaining a well-functioning lab environment because many students take this opportunity to explain quirks and idiosyncrasies about the equipment and common questions about both experimentation and analysis are addressed to everyone at once. It also provides an opportunity for and feeling of cooperation, friendliness, and community amongst students, faculty, and staff. Students comment on this community aspect, frequently and positively, in the course evaluations!

One of the most loved-by-the-students elements of Field Session is the Friday lunches. The department furnishes lunch for the students, faculty, and staff on Fridays for three of the five weeks, with strategically increasing quality of food vendor as the weeks go on. The informal nature of the students and faculty sitting together sharing a meal is invaluable for class morale and community building. Students also use this time to ask specific questions of those who have just performed the experiments they will perform on Monday or Tuesday, adding further to cooperative nature of the course. In addition to this, the department furnishes popsicles to the students on warm days (the lab building can get especially hot with all the steam-related experiments, particularly in July and August!). These are tried-and-true methods of motivating the students, and the social interactions they provide great benefits to both the students and the faculty. Additional ways to motivate students are discussed below in the Recent Innovations section.

**Recent Innovations**

The two primary innovations to the delivery of this course over the past three years are the addition of themes and teams and the introduction of pre-lab videos covering operational procedures. Since the second half of the summer of 2017, Field Session students have been divided into teams based on a theme, such as Harry Potter or Game of Thrones. Instead of being grouped into teams A1, A2, B1, and B2, students were members of houses such as Hufflepuff and Slytherin or Baratheon and Targaryen.

1 We typically have pizza in week 2, sandwiches in week 3, and barbecue in week 4.
This “theming” of Field Session has succeeded in its intended purpose of bringing a feeling of comradery between students grouped together, and an air of healthy competition throughout the course. It has had additional side benefits, such as the development of fun and interesting nicknames and memes (used in presentations or sometimes in reports) as well as the opportunity to integrate popular culture into some of the lectures and weekly class debriefings, which has proven effective in some active learning situations [13-14].

The second major innovation to this course is the introduction of pre-lab videos. These videos are a mix of first-person and third-person clips of the experimental operation, with particular focus on frequently occurring mistakes (e.g., turning on a pump upstream of a fully open rotameter), potentially major problems (e.g., draining the reboiler of a distillation column), and particularly confusing or less obvious aspects to the procedures (e.g., the location of a hard-to-find switch or how to depressurize a non-relieving gas regulator). Since their introduction for only a few select experiments, these videos have been increasingly requested by the students and reviewed positively. While detailed results will be presented in a future paper, this innovation has already led to fewer incidents of minor equipment damage and less frequent “experimental failure”. Preliminary data on lab performance point to potentially greater long-term gains (from the second to the fifth week) on report grades for labs which had pre-lab videos compared to those without.

**Program Outcomes and Recommendations**

One important metric for any core course is the percentage of students who successfully complete the course on their first attempt. Field Session has an incredibly low recidivism rate, with the only (incredibly rare) failures in recent decades originating from either plagiarism or non-completion/-attendance. The average (mean) course GPA is slightly higher than other courses, ranging from 3.08 to 3.32 in recent years, and varies less from year to year than other courses within the core.

When surveyed at the end of the course, student perceptions fall in line with these outcomes. Ninety-three percent of students surveyed from 2012-15 agreed or strongly agreed with the statement “instructors helped me to develop my ‘higher-order thinking’ skills” [10], while more recent surveys have shown that students value the critical thinking workshops. These surveys asked students to rate the value of various aspects of the course, from 1 to 5 (with 5 being highly valuable), and the only aspects to receive an average score of lower than 3.1 in 2018 were the Graphics (3.07), Writing (3.01), and HAZOP/Safety workshops (2.92). The highest rated aspect of the course besides the Friday lunch (4.66) was the opportunity for technical draft reviews with professor specific to the experiment (4.50). A portion of these data is presented in Figure 1.
In addition to these quantitative results, qualitative data has been gleaned from student comments on the surveys to open-ended questions such as “What did you like most about field session?” and “What did you like least…?” Some common, negatively oriented answers to the former question include “That it’s over”, or “The end meeting” while corresponding answers to the latter question might include “Literally everything else”. Nevertheless, there are a number of common positive and constructive answers to these questions as well, including the following representative sample responding to “What did you like most”:

- “Hands-on, similar to industry”
- “Getting to design our own experiments and being held to a high standard”
- “the people I met, the professors, the communication and team skills”
- “the professors make you think”
- “I learned a lot even if I didn’t want to”
- “… working with my peers. I met a lot of people who I probably never would have outside this class”
- “I liked being forced to work hard and apply what I have learned. Working through higher order thinking objectives helped me learn more than I had in normal classes”
- “Honestly the grind and time management skills”
- “Orals. Quick turnaround time left less time for stupidity and messing around”

These last two comments, while constructive, were in fact a bit more commonly found in answers to the second question, “What did you like least about field session?”, as in the following sample:

- “working on 3 labs at a time”
- “the late nights till 2 am”
- “the long nights preparing reports”
- “24-hour turnaround”
- “Monday night preparing orals”
- “so time intensive and I was always tired”
- “the way we had to work 12+ hour days for most of the week”
- “Some of the turnaround times were rough and a lot was expected from us right off the bat but nothing was too horrible”

Clearly the students who have just completed field session have a good deal of complaints, yet the vast majority of it focused on the intense schedule and high demands (as well as about the climate conditions inside the lab on hot days). Yet, even more important than student perceptions immediately following the course are those of alumni. The CBE department surveys alumni regularly with a reasonable response rate (at least around 25%) and field session always filters to the top as the most valuable experience of students’ time at CSM [10].
Alumni from the Chemical and Biological Engineering Department at CSM have long indicated that the Unit Operations Laboratory was invaluable, with many indicating that it was the most important course in terms of preparing them for an industrial or consulting job. Annual alumni surveys include the question (which does not specifically mention the Unit Operations Laboratory): “Which aspects of your education at CSM were most valuable to you in your current career?” Selected responses from the most recent survey appear below:

- “Without a doubt, the Unit Ops lab. The ability to write a report that doesn’t need extensive editing or give a talk that doesn’t embarrass my boss goes a long way towards building job security.”
- “Professors could relate class material to real world experience. Field session was a great class which gave me a dose of what to expect as a professional in the field, presentation, and thinking about exactly what it is that we are doing.”
- “It pains me to say this, but the Unit Ops lab gave a great model of a real world working situation – fast paced, heavy loads, and a focus on professional communication.”
- “My job is very similar to the way field session was run. The teamwork aspect was maybe the most valuable learning experience to me – I need those skills daily.” [10]
- These data reveal that this unit ops course is one of the most highly valued among alumni (as it likely is of many Chemical Engineering programs), but also that this is so not despite the fact but precisely because it is so uniquely rigorous and fast-paced, with increasingly high expectations both of students’ communication skills as well as analysis, higher-order-thinking, and experimental design.

**Program Risks and Potential Disadvantages**

The way this course is organized has many positive outcomes, yet there are nevertheless risks and drawbacks associated with the structure of Field Session. For example, conflicts with internship opportunities, financial burdens, and student complaints on course evaluations do arise. Taking place only in summer sessions often requires students to ask for accommodation with (or otherwise potentially give up) summer internships. This means that many of the seniors take this final course after having participated in their May graduation ceremony! One advantage of this though is that they have hands-on experience from internships performed during the prior summer(s). This can be a benefit to other students, but it can also lead to frustration for many of the seniors, which appears in peer evaluations of some ‘inexperienced’ juniors.

Maintaining all of the faculty support, from the Writing Center to the experiment-to-professor and student-to-professor ratios, on top of expert technical support for a process laboratory, all make this course relatively expensive to deliver. This expense is partially offset with laboratory fees and summer tuition (which is higher than for a regular semester, contributing to some student complaints, below), but this could be a deal breaker for smaller programs. It is possible that teaching assistants may be used to fill some gaps, but likely there will be a corresponding drop in quality of guidance as compared with having faculty instructors in these roles.
Finally, and at least historically, many students can be quick to complain about the difficult and intense schedule and can then express this discomfort in excruciating detail in course evaluations. Expectations for course evaluations around a Unit Ops course should always be managed, especially when making any significant changes to course structure. A better measure will be alumni opinions, with a bit more perspective. Course evaluations will necessarily suffer from providing the students with an uncomfortable, albeit highly effective, learning experience. However, we also have experienced significantly improved course evaluations during 2018’s first summer session simply by promoting positive voices! A few students were commenting that they were having fun and learning a lot. When that was announced in a general meeting and the whole group was asked who else felt the same, a significant majority of the students raised their hands. This led to a noticeable improvement in student attitudes, better than historical course evaluations, and arguably even a higher overall course performance of the students in that particular session relative to past years. This indicates that student attitudes can both be managed to some extent and can also predict course performance.

Conclusions

These methods are most applicable to programs of considerable size, as they have demonstrated scalability over the decades and utility at the current large size of the program. Nevertheless, the authors feel that there are aspects of this model for a Unit Operations lab course which could be useful to any Chemical Engineering program in the United States. The support of other parts of the university, like a writing center or English department, should be leveraged whenever possible.

Finally, the authors would like to point out that that the Field Session course should be in operation during the time that the Chemical Engineering Summer School program will be taking place at the ___ in 2021 and we look forward to providing visits or tours to interested attendees.
Acknowledgements

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References:


