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[1]; students may practice open-ended experimental design[2,3] and use their experimental work to perform detailed data analysis, to develop professional-grade thinking and reporting skills[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 Kolb[6]. The four stages of learning, shown from a student's perspective and in relation to a typical thinking taxonomy, are illustrated in Figure 1.

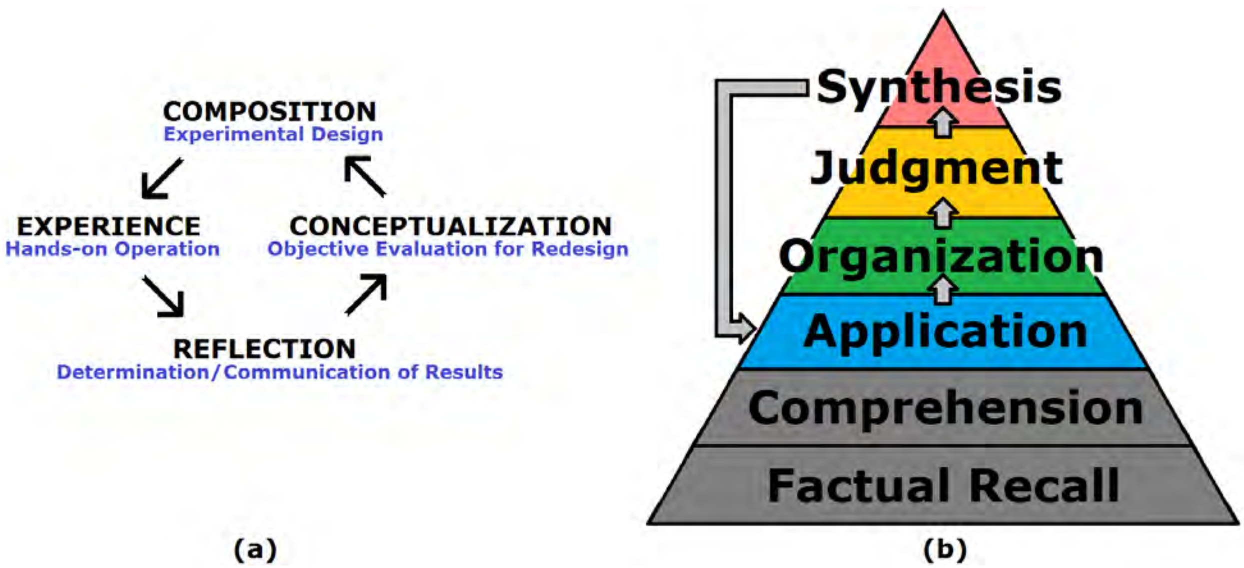

Figure 1: (a) Experiential learning cycle, and (b) hierarchical thinking taxonomy.

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 1: Chemical Engineering Unit Operations Laboratory Experiments at CSM

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

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).

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

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[7] 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

1 Y. H. Elawady, A. S. Tolba, "Educational Objectives of Laboratory Types: A Comparative Study," International Journal of Computer Science and Information Security, vol. 6 (2), 2009, pp. 89 – 96.

2 B. R. Young, H. W. Yarranton, C. T. Bellehumeur, and W. Y. Svrcek, "An Experimental Design Approach to Chemical Engineering Unit Operations Laboratories," Education for Chemical Engineers, vol. 1 (1), 2006, pp. 16 – 22.

3 L. Jiménez, J. Font, and X. Farriol, "Unit Operations Laboratory Using Ill-posed Problems," International Journal for Engineering Education, vol. 19 (5), 2003, pp. 717 – 720.

4 A. M. Abu-Khalaf, "Improving Thinking Skills in the Unit Operations Laboratory," International Journal for Engineering Education, vol. 17 (6), 2001, pp. 593 – 599.

5 R. L Miller, B. M. Olds, "Encouraging Critical Thinking in an Interactive Chemical Engineering Laboratory Environment," Proceedings of the Frontiers in Education Conference, San Jose, CA, Nov. 1994 (no. 24), pp. 506 – 510.

6 D. A. Kolb, "Experiential Learning: Experience as the Source of Learning and Development," Prentice-Hall: New Jersey, 1984, pp. 21.

7 R. L. Miller, J. F. Ely, R. M. Baldwin, and B. M. Olds, "Higher-order Thinking in the Unit Operations Laboratory," Chemical Engineering Education, vol. 32 (2), 1998, pp. 146 – 151.

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