HIGHER-ORDER THINKING IN THE UNIT OPERATIONS LABORATORY

RONALD L. MILLER, JAMES F. ELY, ROBERT M. BALDWIN, BARBARA M. OLDS
Colorado School of Mines • Golden, CO 80401

Most faculty members are aware that too many engineering courses emphasize "plugging and cranking" on well-defined, close-ended, numerical problems at the expense of helping students become better critical thinkers and engineering practitioners. As a result, and in sharp contrast to other professions such as medicine and law, too few of our engineering graduates are capable of immediately practicing engineering when they leave college. Yet, industry expects to hire engineering graduates who can "go beyond the numbers" by understanding how technical results fit into a larger systems perspective, who can integrate knowledge to find new solutions to problems rather than relying on a traditional reductionist approach, and who can communicate the results of their work to many different audiences.[1] In short, they want engineers who can "think outside the box."

In response to these expectations, many of the new ABET Engineering Criteria 2000 features focus on professional practice, including "an ability to design and conduct experiments as well as to analyze and interpret data; an ability to identify, formulate, and solve engineering problems, an ability to function on multi-disciplinary teams; and an ability to communicate effectively."[2]

We believe that the unit operations laboratory provides an ideal setting to help chemical engineering students become better engineering practitioners. At the Colorado School of Mines (CSM), we offer the unit operations laboratory as an intensive six-week summer experience designed to enhance students' higher-order thinking skills and familiarity with many aspects of chemical engineering professional practice, including data collection and analysis, evaluation and interpretation of results to draw meaningful conclusions, and effective communication to a variety of audiences.

As presently taught, the course relies heavily on a constructionist approach—that is, the cognitive theory suggesting that learners construct their own internal interpretation of objective knowledge based, in part, on formal instruction, but also influenced by social and contextual aspects of the learning environment and previous life experiences.[3] This view suggests that students "make their own meaning" of what they are learning by relying on mental models of the world, models that may be correct or may contain strongly held misconceptions.[4] Rather than acting as acknowledged authorities transmitting objective knowledge to passive students, laboratory faculty use coaching and Socratic questioning techniques to help students understand complex technical phenomena by constructing mental models that reflect reality as perceived by acknowledged experts while minimizing models containing significant misconceptions.

__Ronald L. Miller__ is Associate Professor of Chemical Engineering and Petroleum Refining at the Colorado School of Mines, where he has taught chemical engineering and interdisciplinary courses and conducted research in educational methods and multiphase fluid flow for twelve years.

__James F. Ely__ is Professor of Chemical Engineering and Petroleum Refining at the Colorado School of Mines, where he has been since 1981. During his career at CSM he had taught courses in chemical engineering fundamentals and has performed research in molecular thermodynamics.

__Robert M. Baldwin__ is Professor and Head of the Chemical Engineering and Petroleum Refining Department at the Colorado School of Mines, where he has been for 23 years. His research has concentrated on fundamental and applied reaction engineering, and he is currently carrying out research on synthesis and evaluation of zeolite membranes at microgravity conditions.

__Barbara M. Olds__ is Principal Tutor of the McBride Honors Program in Public Affairs for Engineers and is Professor of Liberal Arts and International Studies at the Colorado School of Mines, where she has taught for the past fourteen years. She is chair of CSM's assessment committee and has given numerous workshops and presentations on assessment in engineering education.

In addition to experimental work, extensive use of statistics to analyze and evaluate data and instruction and practice in technical oral and written communication are also important facets of the course. In this paper, we present details of

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the course organization, methods we use to promote higher-order thinking, expected student outcomes, and examples illustrating how students' higher-order thinking and communication abilities develop during the course.

COURSE DESCRIPTION

All CSM chemical engineering students (approximately 90-100 per year) are required to complete a rigorous six-credit-hour summer field session following their junior year in which they spend six weeks conducting, analyzing, and reporting the results of a series of sophisticated unit operations experiments. Expected student outcomes during the course include

- *Reinforcing understanding of basic concepts in momentum, heat, and mass transport, and statistics*
- *Learning how to analyze, synthesize, and evaluate experimental results*
- *Improving technical oral, written, and graphic communication skills*
- *Enhancing team-building and leadership skills*

To facilitate development of each student's engineering abilities, supervising faculty place as much responsibility for the planning, execution, analysis, evaluation, and reporting of experiments on the students as possible. Each student performs eight of the ten experiments listed in Table 1, working in teams of two or three. Teams are randomly sorted from experiment to experiment so that students work with all their peers in the course and each student has the opportunity to serve as a "team leader" on several experiments. Since the students have received extensive team-building instruction and practice in the CSM EPICS (Engineering Practices Introductory Course Sequence) program,[5] no additional team-building work is required in the laboratory. As a capstone project, student teams also design a new unit operations experiment or retrofit an existing piece of equipment.

TABLE 1
Experiments Performed in the CSM Unit Operations Laboratory

☒ Compressible gas flow
☒ Blower and venturi meter
☒ Pump characterization
☒ Shell and tube heat exchanger
☒ Condensing steam heat transfer
☒ Wetted wall column
☒ Continuous distillation column
☒ Tank transient heating
☒ Friction factors and drag coefficients
☒ Gas absorber packed column

TABLE 2
Objectives for the Friction-Factor and Drag-Coefficient Experiment

☒ Develop a friction-factor correlation for pipeflow encompassing the laminar-, transition-, and turbulent-flow regimes
☒ Evaluate the performance of installed orifice meters
☒ Develop a drag-coefficient correlation for particles settling in quiescent fluids
☒ Evaluate the validity and limitations of each correlation

Each experiment consists of the five steps shown below; student teams must satisfactorily complete each step to receive credit for the experiment.

- *"Prelab" preparation*
- *"Prelab" oral presentation to supervising faculty member*
- *Operation of the equipment to collect data*
- *Analysis, synthesis, and evaluation of data including statistical error analysis*
- *Presentation of results orally or in writing, including preparation and review of draft written reports.*

Preparing and Presenting the "Prelab" • The afternoon prior to performing an experiment, each student team meets to become familiar with the general experimental objectives and safety guidelines provided by faculty supervisors (an example set of objectives is shown in Table 2), to study the equipment and how to measure and model its performance, to create a list of detailed experimental objectives, to develop an experimental design for data collection, and to decide what statistical analysis strategies will be used with the experimental data.

We do not provide detailed step-by-step instructions on how to conduct or analyze an experiment—less than one page of written guidelines (including safety issues) are typically available for each experiment. Instead, students are expected to educate themselves on the appropriate background knowledge required to meet each experiment's objectives, using their textbooks and other information sources; faculty supervisors act as coaches or mentors to the teams, but do not portray themselves as authority figures. Faculty rarely answer questions directly, but instead help students find their own answers using prompts such as "How do you know that?", "How would you estimate or measure X?", "Have you considered Y?", "What are the limitations of that correlation?", or "How good is that assumption?"

Early on the morning the experiment is scheduled, each student team presents the results of the "prelab" preparation to a supervising faculty member who questions members of the team on all aspects of the experiment, including background theory, working equations, data collection, measurement errors and data reproducibility, and data analysis and evaluation. At the beginning of the course, students need more direct feedback to help them establish realistic objectives and correctly compute results from experimental data. As the students become more adept at routine data collection and analysis, faculty begin to ask more complex questions to begin the process of nudging students to think in new and more sophisticated ways.

We believe the "prelab" exercise is a crucial part of each experiment because students acquire a good understanding of the experiment and our expectations before beginning data collection. Depending on the degree of preparation and understanding, each team may spend from 15 minutes to 2 hours in this examination; no team is allowed to begin work in the laboratory until the examination has been passed. Our objective here is to ensure that students have thoroughly developed their experimental objectives and their data collection and analysis strategy; the laboratory itself is not the place to begin this process.

Working in the Laboratory • Once they are in the laboratory, each student team controls its own destiny and operates without input from faculty supervisors or teaching assistants (except for potential safety issues). Students make decisions about ranges of data to collect, about the amount of data to collect, and about conducting reproducibility runs. Depending on the complexity of each experiment, they may remain in the laboratory for anywhere from four to eight hours collecting data. They often use laptop computers for "real-time" data analysis, and several of the experiments are computerized for automatic data logging directly into personal computers.

Working with the Data • With data in hand, the team begins the process of data analysis, comparison of results with theoretical predictions or accepted correlations, and statistical error analysis. This is an intense time for the team members—they must either prepare and deliver a 20-minute oral presentation describing their work one day after completing the experiment or must submit a draft written report five days after completing the experiment. In either case, they must complete calculations, develop appropriate correlations of engineering parameters such as friction factors or heat-transfer coefficients, prepare figures and tables of results, develop error propagation and statistical analyses, provide logical explanations for any deviations of their results from expected values, and develop overall conclusions based on evaluation of their work.

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We have three reasons for requiring short turn-around times for oral and written reports. First, the laboratory schedule requires students to move quickly from experiment to experiment in order to complete eight experiments within the six-week course. Second, time demands absolutely require effective teamwork—no individual student alone can possibly complete all the tasks of an experiment. Third, and perhaps most important, we want to encourage students to plan and study the experiment thoroughly during their "prelab" preparation. This allows them to develop their higher-order thinking skills by concentrating on developing meaningful conclusions from their results rather than just reporting routine lists of numerical data.

Communicating the Results • Students produce four oral and four written reports on experiments completed during the course. In addition, both an oral and written report are required as part of the final design project. Oral presentations are attended by other students in the course and by one or more faculty supervisors; presenters are expected to focus largely on the conclusions drawn from their results and reasons for any obvious discrepancies from expected trends. Once again, faculty use Socratic questioning to probe for evidence of analysis, synthesis, and evaluation by student teams. Each written report is submitted first in draft form for review by the faculty supervisor and a technical communication specialist. Draft review meetings are then held with individual student teams to provide feedback and to discuss remaining difficulties in technical and rhetorical content before the final version of the report is submitted for grading.

Other Course Activities • To further help students improve their thinking and writing skills, during the first few weeks of the course we conduct a series of workshops that focus on statistics and data analysis, experimental design, and written communication. For example, as part of the experimental design workshop, we ask students to brainstorm and share ideas for extending the analysis of the experiment they are currently conducting beyond the objectives stated in their "prelab." This exercise works well to help students think and work beyond the obvious outcomes for each experiment and encourages students to "think beyond the box" in the course.

The course culminates in a week-long capstone project in which student teams are asked to design a new laboratory experiment or to retrofit an existing piece of equipment to improve its performance. The design project allows students to apply the knowledge and skills learned in the laboratory experiments in a new engineering context. In recent years, students have designed experimental systems to study gas/liquid flow in horizontal and vertical pipes, gas/solid fluidization, reverse osmosis, air separation using membranes, and transient drying of wet granular solids.

TABLE 3
Bloom's Taxonomy of Cognitive Behavior[6]

Evaluation	Judge the merit or quality of ideas or designs, using evidence
Synthesis	Solve a problem by combining two or more specific skills
Analysis	Explain relationships or make inferences based on data
Application	Apply techniques and rules to solve straightforward problems
Comprehension	Organize facts and main ideas
Knowledge	Recall facts or observations

DEVELOPING, MONITORING, AND ASSESSING HIGHER-ORDER THINKING AND COMMUNICATION SKILLS

As we designed the unit operations laboratory course to help students develop their higher-order thinking and communication skills, we were guided by Benjamin Bloom's taxonomy of cognitive objectives;[6] the taxonomy is also useful as a performance assessment framework to determine whether students achieve the expected outcomes listed earlier. Students are assessed by course faculty (in each "prelab" session, oral presentation, and written report) on their ability to demonstrate a thorough understanding of basic transport phenomena and unit operations concepts and their use of statistics to analyze and evaluate experimental data. Students' communication and team skills are also assessed by the faculty within the context of laboratory work. In addition, each student evaluates the contribution of each teammate after each experiment is completed. In this way, students are individually held accountable for their contributions to the team's success or failure. Students who receive a poor peer evaluation are immediately counseled by course faculty—repeated low evaluations result in an overall grade reduction or withdrawal from the course.

As shown in Table 3, Bloom's model proposes six classes of cognitive behavior, ranging from simple recall of facts or ideas (knowledge) through explanation of relationships and data inference (analysis) to sophisticated value judgments about the quality or merit of an idea using data (evaluation). The term "higher-order thinking" usually refers to the higher three levels of cognitive behavior in the taxonomy—analysis, synthesis, and evaluation.

In this section, we present excerpts from laboratory reports to illustrate how students' thinking develops during the six-week session. The process is developmental, slow, and at times frustrating and painful for some students. But we have found that all students in the course, regardless of academic preparation and background, can improve their ability to think and communicate if given appropriate feedback and encouragement by faculty supervisors and peers.

Lower-Level Thinking • During the first two weeks of the course, students tend to function in modes of thinking that have been reinforced in earlier courses—simply reporting facts and straightforward numerical results from the experiment. We predominately see laboratory reports containing statements such as

- *Our results show that the orifice coefficient is 0.55. In industry, the accepted coefficient is 0.61. Therefore, our results don't agree with the correct value.*
- *The experimental acoustic velocity was found to be 1444.0 ft/sec, which is 27.2% different from the theoretical value.*
- *Our heat-transfer coefficients ranged from 365 to 704 Btu/hr ft^2 °F, which are well within the accepted range of 200-1000 Btu /hr ft^2 °F.*
- *We compared our heat transfer correlation to the accepted correlation. We found that our exponent on the Reynolds number was lower, but the coefficient was greater. The exponent on the Prandtl number was about the same.*

At this point, students believe that reporting results, perhaps with a simple numerical comparison to an accepted value or range of values, constitutes data analysis. Although they don't realize it, the message at this point is "Here's what we got; you (the reader) figure out what it means." Early in the course, students don't yet have the ability to critically analyze their data, to use error and statistical analysis, and to derive meaningful conclusions because they have never been taught how to do it nor were they expected to do it. Previous laboratory and lecture courses reinforced the idea of one correct answer for every problem and the misconception that the teacher is the only authority figure in possession of all knowledge. When students are confronted with "incorrect" results (*i.e.,* results that don't agree *exactly* with theory or accepted correlations), even though the experiment was done "correctly," they become puzzled and often respond with illogical and sweeping conclusions such as "all our data are bogus" or "the experimental apparatus is obviously broken."

The Beginning of Analysis • By about the third week (after completing two oral and two written reports), most students begin to understand how to analyze their data. At this point, we see report excerpts such as

- *Our friction factors ranged from 0.0073 to 0.091 with a mean error from accepted values of 32%. Error propagation estimated experimental errors at 31%. The biggest contribution to the error came from pressure-drop measurements. Finally, we observed that all of our experimental friction factor values were below values from the Moody diagram.*
- *Our measured values of heat-transfer coefficients ranged from 571 to 1079 Btu/hr ft*^{2} *°F and differed from accepted correlation values by 2.6% to 36%. All percent differences were within the estimated error propagation; as a result, we conclude that our measurements are as precise as the instrumentation allows and contain no experimental bias.*
- *Orifice coefficients using velocities measured with the anemometer varied from literature values of 19-66%, while coefficients using Pitot-tube data varied by 8-54%. This difference was attributed to human error in using the anemometer and reading Pitot-tube fluctuations.*

Now students have progressed beyond routine data reporting to include a more detailed comparison with accepted results, which indicates the beginning of legitimate data analysis and the search for trends and correlations among experimental variables. The students' message has become, "Here's what we got, and here's how it compares quantitatively to accepted results." Often, however, inferences that could be drawn from quantitative comparisons of experimental and literature results are implied but not yet explicitly stated. Students at this stage are still reluctant to state definitive conclusions about the data. Instead, we see general statements such a "We conclude our data are unbiased" or "Our results indicate the presence of human error." Ironically, writing quality tends to deteriorate as students are pushed to more sophisticated levels of data analysis and evaluation. Since writing and thinking are so closely connected,[7] students who are in the process of developing new modes of thinking often have significant trouble articulating their ideas.

Moving from Analysis to Evaluation • By the fifth week, students are quite adept at reporting routine results and most are capable of some reasonable data analysis. They are also capable of synthesizing knowledge from different subject areas (*e.g.,* fluid mechanics, heat and mass transfer, statistics) without major difficulty. But developing the ability to evaluate their results critically and to draw definitive conclusions from their work is very difficult for the students, and supervising faculty spend most of their time coaching the teams to help them meet this goal. At this point, the better students begin to write reports containing excerpts such as

- *For the 0.1-inch diameter orifice plate, we found an orifice coefficient of 0.65 with a 95% confidence interval of 0.60 to 0.70, which compares favorably with the accepted value of 0.61. Thus, we conclude that the orifice meter is working properly and operating as expected.*
- *As shown in Table X, the agreement between the measured velocity of sound using conservation of mass and the orifice meter equation varied by less than 7%, indicating consistent experimental orifice meter data. Experimental acoustic velocity results are a function of orifice diameter. This result shows an error in the estimation of the pressure ratio at choking because the acoustic velocity should be independent of orifice diameter.*
- *The experimental friction factor values from the steel tubing tended to lie above the correlated smooth pipe curve, indicating the tubing had an inside roughness greater than*

TABLE 4
Summary of Student Feedback Results

Question	Percentage Disagreeing or Strongly Disagreeing	Percentage Neutral	Percentage Agreeing or Strongly Agreeing
I better understand the differences between lower-order thinking and higher-order thinking.	0.0	12.2	87.8
My higher-order thinking skills have improved.	2.4	7.3	90.3
My knowledge of statistics and error analysis has improved.	2.4	4.9	92.7
My written communication skills have improved.	2.0	6.8	91.2
My oral communication skills have improved.	5.9	5.6	88.5
My ability to work in teams has improved.	7.3	22.0	70.7
I believe this course was worth the time and effort.	7.2	9.8	83.0

> *expected. We calculated the roughness of the steel tubing to be 0.00053, which is 15% higher than the literature value for steel pipe in [our text]. We conclude the tubing has a rough deposit on the inside wall, maybe from hard water.*

Students have now moved beyond data reporting and simple comparisons and have begun developing *inferences* about what the results actually mean. Their message has become, "Here's what we got, here's how it compares to accepted results, and therefore, here's what we think it means." Because most of the students lack extensive industrial experience, the inferences are generally not very sophisticated, but they do help students begin to understand the limitations of published results and correlations and the importance of engineering judgment in professional practice. We also observe that by the fifth week, the quality and depth of writing begins to improve—students are becoming more capable of expressing their newly developed ways of thinking.

STUDENT FEEDBACK ON THE COURSE

At the end of each six-week session, we ask students to provide feedback about what they believe they learned in the course; a summary of results from the first session of 1997 are shown in Table 4. Approximately 90% of the students believed they better understood the concept of higher-order thinking and that their own higher-order thinking skills improved in the course; about the same percentage also believed their oral and written communication skills had improved, while nearly 93% believed their knowledge of statistical analysis improved.

Overall, 83% of the students believed the course was worth the tremendous time and effort involved (approximately 60-80 hours per week). One student commented that "for all the pain and suffering, field session was definitely worth it. I learned more in six weeks than during three years of class." Another stated that "field session was very difficult, but it was also rewarding. I think its focus should continue to stress what will be expected of us on the job." We receive similar feedback from our alumni, a majority of whom list the unit operations laboratory as the most valuable course they took at CSM.

CONCLUSIONS AND RECOMMENDATIONS

The unit operations laboratory course we have described is designed to provide undergraduate chemical engineering students with instruction and practice in developing their higher-order thinking and communication skills. Faculty help students improve these skills throughout the course by acting as coaches and Socratic questioners rather than lecturers. Students are generally not able to effectively analyze and evaluate experimental data when they begin the course, but do improve during the six-week laboratory session. The net result is students who have acquired a deeper and more meaningful understanding of chemical engineering fundamentals and professional practice.

For those faculty who would like to use the unit operations laboratory to promote enhanced higher-order thinking in their students, we offer the following observations and recommendations:

- ► Although the "total immersion" summer session is advantageous for helping our students improve their higher-order thinking and communication skills, our techniques should also work using a conventional laboratory course schedule offered during the academic year.
- ► We know of no techniques that magically help students become better thinkers and communicators—the keys are to set high expectations at the outset of the course and to provide a laboratory setting that facilitates student growth and development by maximizing faculty/student interaction. The "prelab" conference is a crucial part of the course structure because it allows faculty to nudge students toward high levels of thinking and problem solving in each experiment.
- ► Expect that the development of higher-order thinking skills will be a slow and sometimes frustrating process for most students. Be aware of where each student is comfortably functioning on Bloom's taxonomy and push him or her to the next level. Think of the process as building a scaffold one level at a time—each level must be reached and solidified before attempting to move on to higher levels.
- ► Depending on the background and experience of students in the course, instruction and practice in team-building skills may be necessary. Don't group students together and expect they will automatically form a functioning team unless they have had previous practice in doing so.

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