Improving Student Learning in the ChE Laboratory

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Abstract: The unit operations lab brings together a significant number of educational goals for the students: experiencing a broad range of equipment and instrumentation, enhancing teaming skills, learning to analyze experimental data, and developing written and oral communication skills. To help improve the students' overall learning in laboratory so as to better prepare them for industry and/or graduate research, we have (1) created a new lecture course on engineering experimentation to accompany the laboratory, (2) increased the emphasis on experimental planning and data analysis for each lab project, (3) implemented a peer-review and report revision procedure, (4) require students to follow industry standards for recording data in laboratory notebooks, and (5) completely revised the department's Lab Manual to reflect these changes in emphasis. This paper describes the organization and effectiveness of our revised laboratory sequence in comparison with our previous approach.

Introduction

The unit operations laboratory is generally regarded as an ideal setting for students to learn the skills that will help them become better engineering practitioners.[1,2] It brings together a significant number of educational goals for the students: experiencing a broad range of equipment and instrumentation, enhancing teaming skills, learning to analyze experimental data, and developing written and oral communication skills. Because of the large number of goals, it is difficult to attain an appropriate balance among them and to stay within the time limitations of the course. Many engineering departments have sought to make significant improvements in their laboratory courses. Jiménez *et al.*[2] describe a "holistic approach" which incorporates more soft skills such as teaming and communication as well as the global concerns of safety, environmental impact, and trouble shooting. Recently, an increased emphasis is being placed on experimental design[3,4] in part due to the importance of this specific area as explicitly required in the ABET EC 2000 criterion.[5] Other departments are adding elements of process design in an attempt to increase student interest in the laboratory projects.[6]

The impetus for this project came from our desire to improve the students' overall learning in laboratory, so as to better prepare them for industry and/or graduate research. In particular, we wanted to focus on the further development of the students' ability to

- independently plan and conduct experiments,
- statistically analyze and correctly interpret experimental data,
- maintain proper documentation and records, and
- communicate technical information in written form.

We have achieved these goals by making several changes to our 3 quarter chemical engineering laboratory sequence. These changes include:

1. creating a new lecture course on experimental data analysis and interpretation to accompany the laboratory,
2. emphasizing experimental planning and data analysis by setting aside specific times in the laboratory schedule for students to work on this,
3. requiring students to follow industry standards for recording data in laboratory notebooks,
4. implementing a peer-review procedure and requiring students to rewrite their reports following a discussion with their instructor,
5. completely revising the department's Lab Manual to reflect these changes in emphasis.

As a result of these changes, students now obtain a more in-depth experience with each project at the cost of reducing the total number of projects from 7 to 5. We believe this trade-off is justified, since the overall goal is student learning, not the number of experiments accomplished. This paper describes the organization and effectiveness of our revised laboratory sequence compared with our previous approach.

Laboratory schedule

The laboratory course sequence consists of three 10 week quarters starting in the spring quarter of the junior year (1 credit, meeting 1 afternoon per week) and continuing with the fall and winter quarters of the senior year (2 credits, meeting 2 afternoons per week). Each quarter, 50 to 60 students work on projects in groups of three. The students have the option of self-selecting their group, otherwise they are assigned to a group. Each quarter, 5 or 6 faculty members (out of a total of 8 in the department) are involved in supervising laboratory sections. Each section is comprised of 3 groups (9 students). Section assignments are made so that each student group will have 3 different instructors, allowing them to experience a broad range of management styles over the three quarters.

Under the old laboratory sequence, the student groups completed a total of 7 projects over 3 quarters, one in the spring quarter of their junior year, and 3 in both the fall and winter quarters of their senior year. Under the revised laboratory sequence, the total number of projects has been reduced to 5. Thus, the students still complete one project during spring quarter, but only 2 projects in both the fall and winter quarters. In place of the third project, two full laboratory periods have been added to each remaining project for experimental design and data analysis. Table 1 shows a comparison between the schedules under each scheme for the winter quarter.

Table 1. Comparison of laboratory schedule for Winter quarter, which consisted of 3 experiments under the old curriculum and 2 under the new curriculum.

Lab Day	Old Laboratory Sequence	Revised Laboratory Sequence
1	Introduction to course	Introduction to course Design project #1
2	Execute project #1	Execute project #1 (data collection)
3	Execute project #1	Execute project #1 (data collection)
4	Execute project #1	Execute project #1 (data collection)
5	Execute project #1	Execute project #1 (data collection)
6	Execute project #1	Analyze data for Project #1
7	Execute project #2	Design project #2 *Report draft due for peer evaluation*
8	Execute project #2 *Reports for project #1 due to instructor*	Execute project #2 (data collection) *Peer evaluations completed and returned for revision*
9	Execute project #2	Execute project #2 (data collection) *Reports due to instructor*
10	Execute project #2	Execute project #2 (data collection)
11	Execute project #2	Execute project #2 (data collection) *Graded reports from project #1 returned and discussed with instructor*
12	Execute project #3	Execute project #2 (data collection) *Revised report #1 due to instructor*
13	Execute project #3 *Reports for project #2 due to instructor*	Analyze data for project #2
14	Execute project #3	Prepare group presentation of project #1 *Report draft due for peer evaluation*
15	Execute project #3	Oral presentations to students and faculty *Peer evaluations completed and returned for revision*
16	Execute project #3	Oral presentations to students and faculty *Reports due to instructor*
17	Oral Reports	Oral presentations to students and faculty
18	Oral Reports	*Graded reports from experiment #2 returned and discussed with instructor*
19	Oral Reports	Work on revisions/additional experiments
20	*Reports for project #3 due to instructor*	*Final revised report due to instructor*

At the beginning of each project the students now focus on establishing their own goals for the project and developing an experimental plan. The students then document their objective and plan in a memo to the instructor and, in some cases, present their experimental plan to other students in their section. At the end of the project, the students have a lab period during which they can work together on completing the data analysis, with an emphasis on quantifying the experimental uncertainty in their data.

The other major change has been the explicit inclusion in the schedule of peer review and report revision. In addition, a day has been allocated toward the end of the quarter for students to collect additional data to augment their final revised reports. We found that quite often students would want to draw conclusions that their data did not support. This additional day for experimentation allows students the opportunity to collect the additional data they may need in order to draw a specific conclusion.

Experiment design and data analysis

One of the primary goals of the revised laboratory sequence was to emphasize the importance of setting project goals, planning experiments, and properly analyzing data. The ability to statistically analyze data and properly design experiments to maximize the yield of information is something that should be common to all engineers. Under the previous sequence, we found this to be one of the students' weak areas. Therefore, two changes were implemented to strengthen their abilities in this area. First, we made this an explicit part of each laboratory project. At the front end, the students are now required to develop (in conjunction with their instructor) the goals and experimental plan for the project. At the back end, the students have a laboratory day explicitly scheduled for data analysis. Second, we added a new course to the curriculum, *Data Analysis and Interpretation*, to provide formal training in these concepts during the first quarter of the laboratory sequence. This new course was added at the same time other revisions were made to our curriculum such that the number of total credit hours required was not modified.

Although the students are required to take a quarter of statistics, there appeared to be very little connection between the concepts learned in that course and the analysis necessary as part of the laboratory projects. Also, despite the widespread use of Design of Experiments (DOE) in industry and the desire of many of our employers to find students with a background in DOE and statistical analysis, our students generally did not have any formalized training in this area unless they selected an elective course on this topic which is periodically offered in the mathematics department. Thus, the new course addresses topics not only related to data analysis but also other topics related to experimentation and measurement. The topics of this course include the following:

- Basic issues in error analysis (definitions, sources of error, etc.)
- Calculation and meaning of uncertainty
- Correlation and Regression
- Other issues in statistical analysis of data
- Statistical Design of Experiments

- Instrumentation (pressure, temperature, and flow measurement)
- Oral and written communication

Aside from DOE the students had previously been exposed to most of the topics relating to statistical analysis. So, the emphasis in the course was on applying these methods using multiple examples. The expectation was that this would help the students see the connections between the statistics they had learned previously and the data analysis necessary for their laboratory projects.

The response from the students about the new course was mixed (based on oral feedback and the course evaluations). Some students thought the new course was a waste of time since most of the material (at least in terms of data analysis) had been seen before. Others, however, appreciated the review of statistical concepts and the chance to see applications of the material. This mixed response may be correlated to the time lapse between their having taken the statistics course and this new course. Approximately half of the students had taken the statistics course the previous quarter while the other half had taken the course 2 quarters earlier. All of the comments pertaining to DOE were very positive.

The six faculty involved with lab during spring 2003 were asked to evaluate student work in the laboratory relating to the topics taught in the new course on scale of 1 (poor) to 4 (very good). Comparisons were between the most current group of students in the laboratory who had taken the new course and the previous group of students who did not take the new course. These evaluations were completed during the summer after the first quarter of the laboratory course but before the second quarter for which most of the changes in the laboratory sequence were implemented. The results are summarized in Table 2.

Table 2. Summary of assessment of Data Analysis and Interpretation course.

Skill	Rating of students without Data Analysis Course	Rating of students with Data Analysis Course
Demonstrated the ability to plan and design experiments*.	2.50	2.50
Demonstrated the ability to calculate/estimate uncertainty and correctly use error bars.	1.83	3.00
Incorporated uncertainty and error appropriately into the discussion of data and the explanation of trends.	1.67	2.67
Demonstrated the ability to correctly perform regression analysis and appropriately fit data with a curve or line.	2.50	2.67
Expressed the need to include statistical analysis as part of the experimentation program.	1.67	2.33
Recognized the appropriate use of instrumentation and the associated benefits and drawbacks.	2.25	2.25
Produced a written report with the appropriate content and structure.	2.50	2.67
Delivered an oral report with the appropriate content and structure.	3.17	3.17

*Note that at the time of the assessment, the students had not yet had the opportunity to plan experiments in lab.

No significant difference was found in the areas of instrumentation use, oral report quality, and written report quality. However, in the area of data analysis, some differences were observed. The faculty found an improvement between the current students and the previous students in their ability to calculate/estimate uncertainty, correctly use error bars, incorporate uncertainty and error into the discussion of data and the explanation of trends, and to include statistical analysis as part of the experimentation program.

The faculty observed no change in the students' ability to perform regression analysis and appropriately fit data with a curve or line or their ability to plan, which has traditionally been strong. In addition, the students demonstrated no improved ability to design experiments. This is because at the time of the survey, the students had not yet had an opportunity to apply these skills. More recently, during the fall and winter quarter laboratory, the students have been able to apply DOE to the projects. Although we have not formally assessed their ability in this area, anecdotal evidence indicates that the majority of the students are able to apply DOE to the experimental plan.

Regarding the areas in which improvements were noted, the students having taken the laboratory course did show more appreciation for the need to use statistical analysis, although some students did not enjoy seeing material on statistics a second time. Moreover, these students demonstrated a higher level of competence using analysis tools in the laboratory course as compared with previous students. In addition, since the faculty knew the students should be familiar with the application of statistics to experimental data, it was easier to discuss these issues with the laboratory groups. Thus, the addition of the new course is showing some positive effects, and the weak areas are being properly addressed. The faculty evaluation of students will be repeated after the third quarter of the laboratory course and again this summer for the next group of students.

For the next offering of the new course, more examples will be used to demonstrate the application of statistical techniques. Also, some of the issues relating to error and uncertainty will be linked with the discussions of instrumentation.

Technical communication

The ChE Laboratory course sequence has an extensive writing component. Each student is required to write an individual report for the first four projects. The final project report during winter quarter is a group formal report. In addition, following each laboratory period, the group is required to submit a one page memo summarizing their accomplishments for that day, including data collected and any analysis completed. In order to improve the students' ability to effectively communicate written information, we have implemented both a formal peer review process and a required rewriting policy. Several authors[7-9] describe alternative approaches for incorporating and improving communication skills in the ChE Laboratory including the use of peer review.[10]

During the peer review process the students learn how to perform a critical review of the work performed by others and how to give constructive feedback. Once the students have received

Table 3. Guidelines for preparing, reviewing, and revising reports.

Initial report preparation

1) Prepare the report(s), of the type assigned by your faculty supervisor. Be sure to proof read your reports. This report must be complete and of a quality consistent with what you would turn in to your instructor. Failure to provide a completed copy for peer review will result in a 10% (1 letter grade) penalty on your final grade.
2) Give a copy of your report to the students assigned to review your report and give a copy to your instructor.
3) Review the two reports that you have been assigned. Be sure to provide as many helpful comments as possible. You should mark directly on the manuscript, and you must prepare a 1-2 page summary of your comments.

Revising your report

4) Revise your report based on the peer reviews.
   a) Prepare a 1 page summary of changes that you made as a result of the peer review.
   b) Proof read your report one final time before turning it in.

Submission of your report

5) You should turn in the following:
   a) Revised report.
   b) The 1 page summary of changes that you made as a result of the peer review.
   c) The original reports given to the reviewers (with their markup).
   d) The separate written comments provided by the reviewers, so they can receive credit for their work.

Understanding how to improve your report

6) Meet with your instructor to discuss your graded report and ways to improve the technical presentation and writing style.
7) It may be necessary to rewrite your reports and/or collect additional data to support your conclusions.

their peer reviews, they revise their reports prior to submitting them to the faculty. The students are thus able to learn from the mistakes of others (by completing a peer review) and from their own mistakes (by having their own work reviewed by a peer). This is an important skill that is seldom emphasized in the typical curriculum.

The peer review process is first introduced to the students in the Data Analysis and Interpretation course. Further instruction is given by the individual instructors, who will often meet with their laboratory sections to further discuss and critique previous examples of both good and poor reports. The students are given specific instructions for preparing, peer reviewing and revising their reports as shown in Table 3.

To assist with the peer review, the students are given a Peer Review sheet, which directs them to consider the most important parts of the reports (as opposed to just correcting grammar). Miller and Williams[11] provide complete details of our approach and the peer review sheet in another paper at this conference.

In addition to the formal peer review, we have required each student to revise his/her reports following a one-on-one meeting with their instructor. One of the issues in the old laboratory sequence was that once the reports were turned in, the project was considered finished by the students. Thus, further learning opportunities were minimized. Due to the tightness of the schedule, it was typically impractical to require students to revise their reports. In fact, by the time the reports were graded and returned, the students were already in the midst of writing the next report. Thus, although the students received feedback on their reports, including the quality of the data analysis and interpretation and the reasonableness of their conclusions, they did not incorporate that feedback into this report by resubmitting and seldom integrated these ideas into their subsequent reports. By requiring revisions, we effectively close the feedback loop and ensure that the students address the deficiencies. Preliminary results indicate that this also improves future reports, since the students have been forced to consider and address these comments.

The one-on-one meetings with the instructor have proven very effective in having the students address concerns from their initial draft. The students are much more likely to address deficiencies when they are discussed with the instructor as opposed to simply returning the reports with written comments to the students. This individual discussion time allows for the student to ask clarifying questions and often becomes a tutoring session in which very specific aspects of any deficiencies are addressed. Many of the students are appreciative of the opportunity to discuss their reports with their instructor. For the group reports, the instructor meets with all group members simultaneously to address any concerns within the report. In all cases, when the reports were resubmitted, the students generally addressed all of their instructor's concerns; however, broader comments on writing style were neglected in some cases.

Student feedback includes the following comments:

- "I feel that having to do two labs rather than three really helped with the feedback process. I liked the fact that we were able to have both peer reviews and professor reviews before we submitted the final copy. Taking the time to sit down with the professor and talk about the report(s) really helped me, rather than being rushed through three experiments in 10 weeks."
- "Love the changes made to the lab curriculum. I learn much better with the ability to get feedback on my reports and make changes."
- "I enjoyed being able to resubmit the report after reviewing comments from professor (instead of resubmitting only once after the peer review), because you never know about peer review comments."

Conclusions

Although formal evaluation of these changes is ongoing, preliminary analysis indicates that these modifications are, indeed, improving student learning during the ChE laboratory sequence. The students are more consistently and appropriately applying statistics to their data analysis and drawing suitable conclusions from the data. In addition, their writing and communication of technical information have improved. The areas of experimental planning and design of experiments continue to offer the most opportunities for improvement. As we seek to further improve the laboratory sequence, this will likely be a focus area.

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