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Expanding chemical engineering laboratory course design for next-generation engineers

Jacqueline Mohalley-snedeker (Senior Academic Professional)

Jacqueline Mohalley Snedeker is the director of the Technical Communications Program in the School of Chemical & Biomolecular (ChBE) at Georgia Tech. One key aspect of the program is its integration of communication instruction into the core ChBE curriculum. Rather than simply teaching a stand-alone communications course, Ms. Snedeker collaborates with other ChBE faculty to incorporate instruction on written, oral, and visual communication, as well as critical thinking, into required courses. She teaches 190+ students per year and assesses over 150 reports and posters and 120 presentations each semester. She also provides instruction on technical communication in courses such as CETL 2000 CBE, which is required for undergraduate course assistants. Ms. Snedeker also assists students with graduate school essays, fellowship applications, and resumés and cover letters.

Benjamin Galfond (Associate Academic Professional)

Benjamin Galfond has been at the Georgia Institute of Technology since 2016. He is an Academic Professional in the School of Chemical and Biomolecular Engineering, where his duties include managing and teaching senior-level laboratory courses.

Expanding chemical engineering laboratory course design to cultivate next-generation engineers

Abstract
Undergraduate laboratory course design has traditionally focused on an experiment and report pairing that can seem resistant to meaningful evolution. The expansion of tasks and assessments beyond this paradigm allows students to focus on process, not just product. This process includes better preparation to safely perform the experiment, requires more advanced understanding of the experimental concepts and results, and introduces students to professional tasks and skills (such as communication skills and teamwork) crucial to post-graduate success. This paper will describe and attempt to quantify pedagogical techniques to broaden lab courses to better prepare students for post-graduation success.

Safety Analysis: While pre-lab meetings and video introductions are not uncommon, a more active engagement in the form of a Job Hazard Analysis (JHA) requires students to not only describe what steps to undertake to meet their objectives, but also to hypothesize on the means and the results of their actions. By completing a JHA, students are not only familiarized with a professional task that is ubiquitous in industry, but also begin developing a mindset that safety must always be an imperative consideration. While JHA effectiveness in industry has been documented, the short-term efficacy of this assignment can be measured with year-to-year comparisons of pre-lab grades and direct observation of student preparedness.

Multi-modal Communication and Teamwork: A report is the most common work product, though this can evolve past an assessment of technical understanding and become an instructional tool to develop the professional communication skills prized in both industry and academia. To this end, the senior lab class, the Unit Operations Lab (ChBE 4200) in the School of Chemical & Biomolecular Engineering at Georgia Tech, is co-taught by a technical instructor and an instructor trained in English and rhetoric; communications instruction is embedded within the curriculum. As students receive instruction and grading explicitly on their writing and communication skills, it will be possible to quantitatively examine improvements across four consecutive assignments. Replacing some reports with research posters introduces students to a new mode of communication, presenting new constraints and options to further diversify how data may be analyzed and conveyed to different types of audiences, which aligns with ABET Student Outcome 3: an ability to communicate with a range of audiences. In addition to communication skills, students are also encouraged to develop their teamwork and leadership skills by (1) including a leadership role as part of the course both through lectures and in-class activities on leadership styles and (2) requiring students to write reflective leadership summaries.

Presentations Informed by Feedback: With thoughtful sequencing, more can be gleaned by having students reflect upon their graded work and deliver either individual or group presentations. This structure not only encourages student reflection upon any errors or inadequacies in the written report that would otherwise have far less instructional value, but also allows the development of both critical thinking and professional communication techniques crucial to career success.

By moving beyond the traditional format of instructional lab courses, instructors use deliberative course design to foster student growth into complete workforce-ready engineers.

Introduction and Course Design

It is no secret to anyone involved in either engineering-related industries or engineering education that employers place a large emphasis on professional skills; indeed, surveys show that overall, employers want their newly hired engineers to walk in the door with the ability to communicate, lead and participate in teams, set priorities, and adapt to new situations. Engineering students as well as recent graduates also recognize that learning and beginning to master these skills in their undergraduate education will be key to both getting their first job and, perhaps more importantly, to advancing in their career. For instance, regarding the need for professional skills on the job, Nicometo and colleagues reported that, in an NSF-supported survey, engineers employed in small and large firms alike reported that "above all other skills required to be an 'effective engineer,' communication was ranked as "essential" by over 60% of our survey respondents." [1].

When ABET adopted Engineering Criteria 2000 [2], which focused more specifically on professional skills in demand by employers, many engineering departments continued their efforts to incorporate instruction on these skills into their curriculum in various ways. Some relied on stand-alone courses or workshops [3], [4], whereas others integrated the teaching of these skills into courses such as senior design as well as lab classes [5], [6]. The majority of these initiatives, especially those involving instruction on communication skills, relied on hiring graduate students from English departments or other outside units to handle the main instructional components as well as the grading. Others used these humanities students and/or humanities faculty to train engineering faculty in how to best teach and assess professional skills within core engineering courses [7].

In contrast, in the School of Chemical & Biomolecular Engineering (ChBE) at Georgia Tech, the approach has been to hire a professional trained in English and rhetoric as an in-house ChBE faculty member and in this way develop an in-house technical communications program specifically targeted towards teaching chemical engineering students best practices and common methods of discourse within the field. Our in-house program has been in existence since 1997 and has primarily focused on the senior unit operations laboratory course, ChBE 4200, to teach technical communication skills.

The structure of the lab class is as follows: students work in teams of three to perform six experiments and to produce four lab reports, two posters, and two oral presentations. These assignments build upon each other to allow students to apply the feedback they receive on a report, for instance, and apply it to a presentation. In this way, students are not only exposed to various types of communication that are prevalent in both industry and academia, but also learn how to adapt their message and communication style for different purposes and audiences.

The course is co-taught by a technical instructor with training in chemical engineering and by the in-house technical communications faculty member. Students do produce written reports and deliver presentations in other core courses earlier in the curriculum, but this is the only course in which communication receives focused instruction. Additionally, communication effectiveness makes up a significant portion of the grade. Each deliverable that the students produce is graded by both the technical instructor (or a ChBE teaching assistant) and by the technical communications faculty member. Separating the communication assessment from the technical assessment allows students to isolate communication-related areas that need improvement. Overall, communication effectiveness makes up about 35% of the grade in the course. While the technical content of each lab experiment dramatically differs, as the communication remains a constant, a more precise grading scheme is possible. Technical rubrics must remain broader to accommodate unique technical aspects of each experiment. Rubrics for technical content and written effectiveness are shown below.

Technical Content – Lab Report

ABSTRACT ____/10

_____ Well done; clearly summarizes the relevant material
_____ Too generic; insufficient economy of prose (too much like the Introduction)
_____ Insufficient quantification
_____ Does not stand alone
_____ Unclear description of the results and their meaning
_____ Other, see comments in report

BACKGROUND (INTRO, THEORY, EQUIP AND PROCEED, REF'S, NOMENCLATURE) ____/15

______Well done; reader prepared to move on to Results section
______Objectives not adequately or specifically stated
______Background not adequate or appropriate for audience of ChBEs
______Need to cite and discuss more literature references
______Needs more (or less) details of theory
______Needs more (or less) details of equipment/procedures
______Other, see comments in report

RESULTS & DISCUSSION ____/20

_____ Well done; results and their significance clearly communicated
_____ Unclear presentation of results or important details missing
_____ Tables and/or graphs not used effectively to communicate results
_____ Insufficient discussion of results
_____ Interpretation of results is not logical or reasonable
_____ Inadequate discussion of error or error analysis
_____ Other, see comments in report

CONCLUSIONS and **RECOMMENDATIONS** ____/10

_____ Well done; conclusions and recommendations clear and informative
_____ Conclusions do not follow from results
_____ Conclusions lacking in substance (just restating basic results)
_____ Recommendations too generic or of little help
_____ Other, see comments in report

DATA, SAMPLE CALCULATIONS, and MISC. ___/10

_____ Well done; data well organized and sample calculations clear and complete
_____ Data poorly organized, incomplete, or not included
_____ Original data sheet missing
_____ Sample calculations missing, incomplete, or incorrect
_____ Sample calculations unclear (unable to follow calculations to check accuracy)
_____ Other, see comments in report (includes professional behavior in the lab)

Total (Technical) ___/65

Figure 1. Technical content grading rubric.

Writing Effectiveness—Lab Report

I. Clarity of Style

A. Structure/Organization ***(10 points)***

- Within all sections, information is presented in a clear and logical manner; each section achieves its rhetorical purpose (e.g., abstract provides a concise summary; intro motivates the study properly, etc.) **(10)**
- Most sections present information in a generally clear and logical manner, as well as achieving their rhetorical purpose; may be some cohesion problems **(7)**
- Although a few sections may achieve their rhetorical purpose, the flow of information is muddled or lacks a clear logic **(3)**

B. Paragraphs ***(5 points)***

- Paragraphs are focused, developed, and intentional; the point and purpose are clear. **(5)**
- Paragraphs are mostly focused, developed, and intentional, but the point is unclear or not fully developed. **(3)**
- Paragraphs are sometimes effective, but most are underdeveloped or weakly unified. **(1)**

C. Flow and Transition ***(5 points)***

- Good use of logical and appropriate transitions between paragraphs and between sentences within paragraphs; tables, figures, and equations are introduced and explained. **(5)**
- Some transitions, but not always logical or appropriate; some tables and figures are not adequately introduced or explained. **(3)**
- Transitions weak or absent; tables and figures are simply "dropped" into the text without introduction or are not adequately explained. **(1)**

D. Sentences ***(5 points)***

- Sentences are direct (short subjects that are close to the verbs), concise, and logical (old info. first), and exhibit accurate and precise word choice, as well as variety in sentence beginnings and choice of transitions. **(5)**
- Quality of sentences is uneven; many sentences are direct, logical, but many are not; may be wordy or unclear (**3)**
- Sentences are very wordy; structure is illogical or unclear; repetitive sentence beginnings. **(1)**

II. Conventions of Correctness (Mechanics of Writing)

Grammar, Punctuation, Spelling, Editing ***(5 points)***

- Lab report is acceptably free of mechanical errors and errors of oversight (i.e., typos). **(5)**
- Report exhibits some mechanical difficulties or sloppy editing; occasional grammatical, punctuation, spelling errors (e.g., prepositions, articles, commas, agreement, tense); every page has 1-2 errors. **(3)**
- Frequent major and minor mechanical errors; extremely sloppy editing; problems impede meaning; more than 4-5 errors per page. **(1)**

III. Document Design (Formatting)

"Look" of Report ***(5 points)***

- Title information (at top of first page), figures, tables, and equations are neat, precise, and follow conventions of the profession (e.g., figures labeled properly, tables formatted correctly, etc.); references adhere to proper format; page numbers properly formatted. **(5)**
- Some unconventional or inconsistent presentation of titles, figures, tables, references, citations, page numbers, or equations. **(3)**
- Tables, figures, captions, and so on do not meet conventions or standards of the profession; references missing or sources not cited properly; missing page numbers. **(1)**

Total (Writing) **_______/35**

Figure 2. Writing effectiveness grading rubric.

The approach to technical communication instruction within the course is threefold: direct instruction through lectures and workshops; individualized instruction and feedback through writing conferences; and detailed evaluation using both written comments and the rubrics shown above.

An additional ABET outcome readily addressed and integrated into the lab class as a professional is process safety. Aside from the ethical obligations to both teach safety as a core concept for future engineers and the onus to keep instructional laboratory classes as safe as possible, hazard analysis has long been recognized as reinforcing basic principles [8]. With such a confluence of reasons to include safety in the undergraduate curriculum, the question then becomes how best to do so. The two common approaches to safety instruction at the undergraduate level has been as either an integrated theme throughout the curriculum or as a discrete course [9]. The clear solution may then be to take both approaches, though adding new safety concepts into content dense courses may prove challenging [10], [11]. Meeting this challenge can improve educational outcomes [12], and thus opportunities to incorporate safety into course design should not be neglected. Integration into a lab class can also expand student perception of practical safety concepts from general lab safety to include hazard analysis akin to government mandated industrial standards [13].

Lectures and Workshops

A central challenge is to convince the students that professional skills such as communication, critical thinking, and safety awareness are not just tangential to the curriculum, but instead are an essential component of their training. We thus begin the course by sharing data from the National Association of Colleges and Employers' (NACE) annual Job Outlook survey, which cites problem-solving skills and communication skills as two of the top qualities employers seek in new hires [14]. We then show students a survey [15] in which science and technology sector employers consistently ranked communication skills as very important attributes for new hires. Students are initially surprised by these survey findings, but eventually they realize that employers do not want to hire a person who just has superb technical skills. Instead, a successful next-generation engineer must also be able to interpret and defend results and deliver the "bottom line" to a variety of audiences across multiple platforms.

In the lab, we teach critical thinking skills in conjunction with communication skills since one of the best ways to learn a concept thoroughly is to write or speak about it. Using an interactive, discussion-based style, we emphasize that writing and speaking can be powerful tools to work through experimental problems, to go a little deeper than just the immediate surface answer. One of the first lessons students learn in the lab is that the goal is not necessarily to get the "right" results, but to explain and interpret the results that they did obtain (even if the results are "wrong.") To this end, we show students examples of successful and unsuccessful lab reports so that we can discuss effective ways of incorporating critical thinking into their writing. We have also developed a course style guide that includes the guidelines for written lab reports as well as examples of each lab report section.

Writing Conferences

A vital element in this approach is that students receive ample opportunities for feedback and continuous improvement throughout the course. Unlike a course in which only one or two written assignments are given, our lab class implements a cycle of feedback on the draft, opportunity for revision, evaluation of the final copy, followed by an opportunity to improve upon any weaknesses in the next lab report, the next poster, or the next presentation.

To this end, student teams are required to come in for a consultation on at least one of the two early lab report drafts during the semester. During the 45-minute consultation, the technical communications faculty can address individualized writing needs while simultaneously reinforcing concepts taught during lecture. Writing conferences are interactive, and students are required to bring specific questions to the conference so that they can direct the agenda for the conference. It has been shown that writing conferences increase learning by allowing students to access an actual listener [16]. Another study by Ekholm and colleagues noted that "positive student perception" of feedback on writing was a key factor in improving students' confidence in their own writing abilities; this study also found that the most preferred type of feedback was through personal conversations with an instructor [17]. Notably, many lab groups (around 50%) come in for more than just the required conference; some groups find the writing conferences so useful that they schedule a conference for every lab. Although labor-intensive, we believe that providing feedback on drafts through interactive writing conferences is one of the most effective tools we can use to help students improve their writing effectiveness. Student feedback has shown this to be true as well, as seen in these anonymous comments from the end-of-the-semester course survey:

> *The writing conferences organized by this instructor were probably the best aspect of the course, as they were a very efficient way to improve learning.*
>
> *Writing conferences were incredibly useful in providing feedback. I feel that I learned much more in the course due to my ability to go in for writing conferences, discuss room for improvement, and directly apply it before turning assignments in.*
>
> *Writing conferences were so great. A great resource to take advantage of. {The instructor} did a wonderful job giving constructive criticism and they always resulted in final products that were so much better than before the conference.*

Evaluation and Assessment

To determine whether our focus on professional skills such as communication is positively affecting student performance, we can look at improvement of scores over a semester. Figure 3 below shows how average writing scores changed over time in four different semesters (note that lab reports are due every two weeks.)

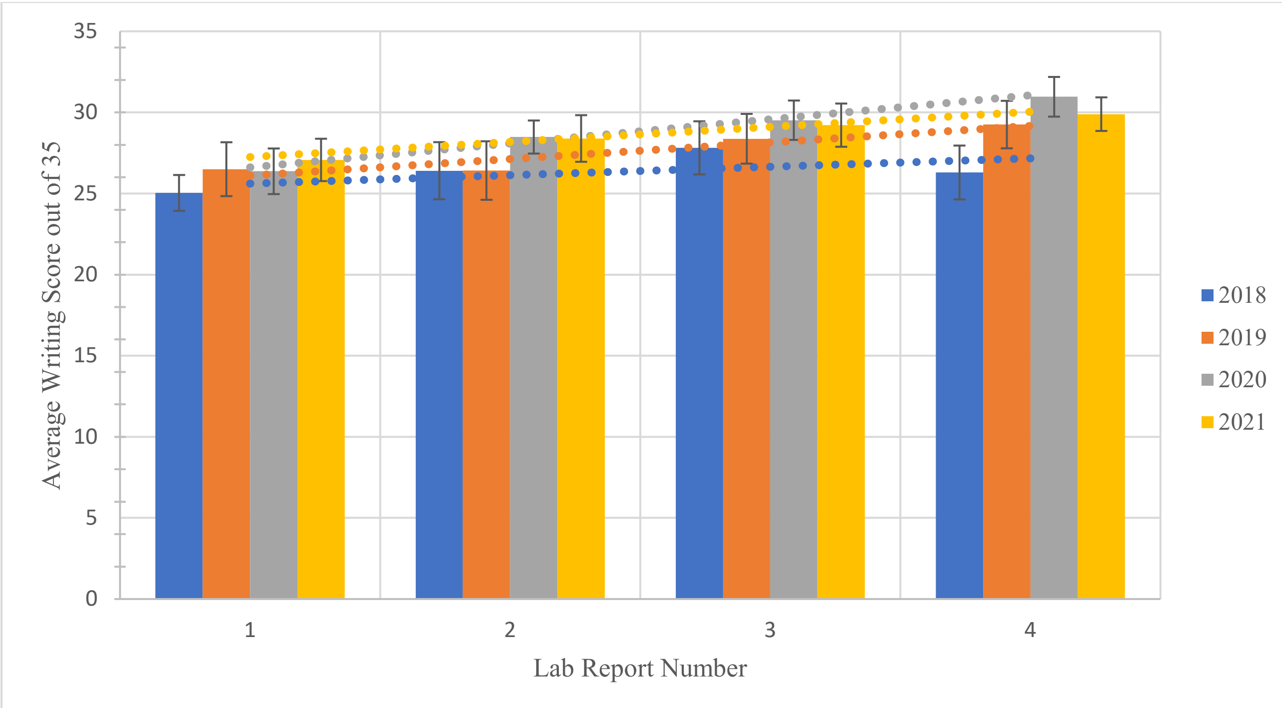

Figure 3. Shows changes in the writing score on lab reports over time in four different semesters with 95% confidence intervals.

Figure 3 indicates that writing scores improved by about 11% from Lab 1 to Lab 3 in Spring 2018. That semester, the Lab 4 grades decreased from Lab 3, possibly because the Lab 4 due date immediately followed spring break or because of conflicting deadlines in other senior classes. All other years saw consistent improvement on each report: in Spring 2019, writing scores improved by about 10% ($p = .014$) from Lab 1 to Lab 4, Spring 2020 saw a 17% improvement ($p = 5.7*10^{-6}$), and Spring 2021 had a 10% increase ($p = .001$). It is also possible this increase would come from natural self-improvement without specific instruction. While we cannot ethically deny instruction to students to test this possibility, expecting an increase in writing performance without a specific communications rubric and instructor feedback seems implausible.

To evaluate whether the communication instruction affected the technical performance, we also analyzed the change in average technical scores (out of 65 points) over time for the same four semesters, as shown in Figure 4 below.

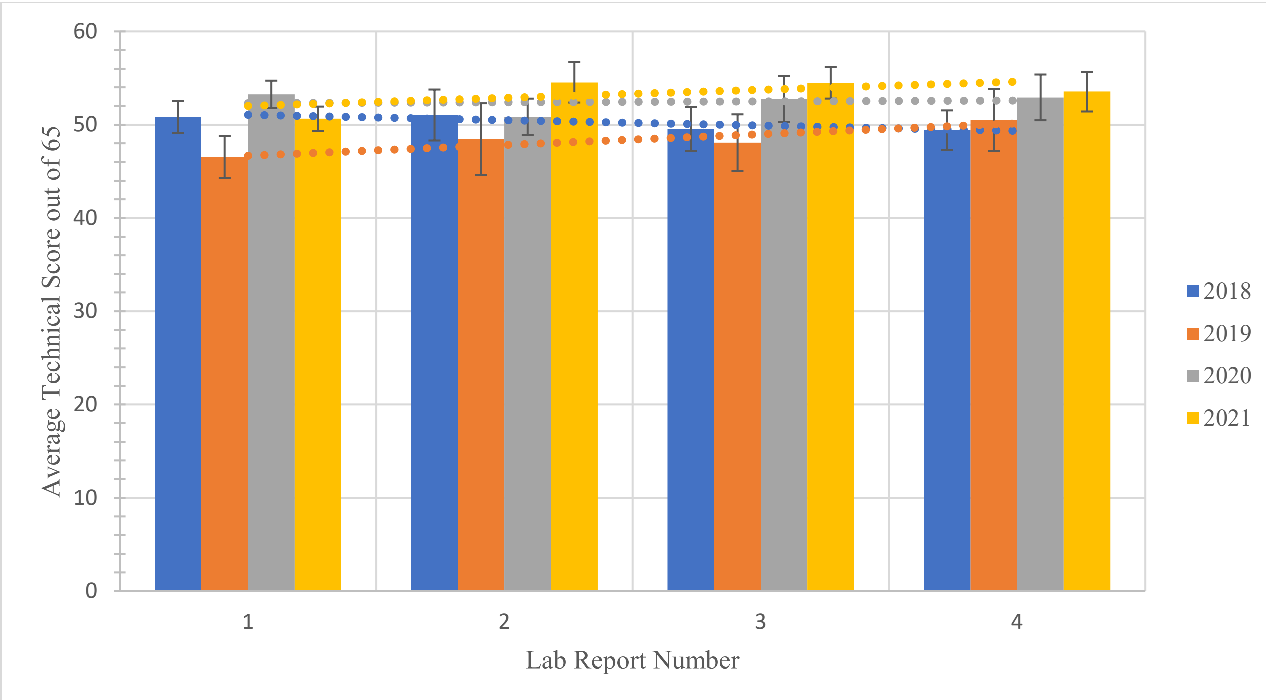

Figure 4. Shows changes in the technical score on reports over time in four different semesters with a 95% confidence interval.

As Figure 4 shows, the technical scores show only minor improvement over the course of a semester, and with more variability due to changing technical topics every lab. Notably, all groups are on different lab schedules; therefore, one group's Lab 2 may be more difficult than another group's Lab 2. 2018 saw a slight decrease in scores throughout the semester, though this fell within the margin of error. In 2019, the average technical content scores improved from 46.5/65 on Lab 1 to 50.5/65 on Lab 4. In 2020, the technical scores dropped slightly from Lab 1 to Lab 2, but then increased by about 5% from Lab 2 to Lab 4. Scores in 2021 improved after Lab 1 and then plateaued for the remainder of the semester. These data are consistent with our contention that instruction and feedback specifically on communication skills is what leads to an improvement in student scores, rather than a change in experiment content or a natural trend of self-improvement over the course of the semester.

Another key aspect of the course involves the use of oral presentations, which is an essential skill to develop for any position in industry or academia. Students receive their graded reports back before they deliver the presentations, thus enabling continuous improvement based on evaluation of the written report. Moreover, all students give both an individual presentation and a team presentation. We record all of the individual presentations and require students to watch their videos and then submit a self-evaluation assignment in which they assess their presentation strengths and weaknesses. Indeed, other studies have shown self-reflection assignments to be a useful tool to "promote student awareness of non-technical skills, motivate students to set personal goals to progress in their skill development, and to enhance student confidence in their self-efficacy related to non-technical skills" [18].

Anecdotally, students have mentioned that while this assignment can be painful, it provides a very useful tool for self-reflection and self-improvement. Notably, presentation scores increased in recent semesters by about 4-6% from the first presentation to the second presentation.

Student comments about the content and structure of the communications component of the course are positive, with end-of-the-semester survey rankings for the course and the technical communications instructor about 4.8 out of 5, where an average score at the institution is about 4.3. A sampling of comments from 2019 indicates student reaction to the communications component in particular:

> *As someone who hated English class in high school, the writing component of this course was actually…enjoyable?*
>
> *I do really believe that my communication skills really improved because of this course. I really like the fact that we had to do presentations, posters, and reports.*

Pre-lab Assignments

While the concept of a preparatory assignment before a lab class is ingrained in many curricula, the form can often vary. Content and delivery method at a single institution likely even varies between courses and instructors. To take best advantage of a limited time in the laboratory, students should have an understanding of the tasks they must complete, and hopefully why, before they begin. While failing to understand the experiment being performed is a pedagogical concern, if students are unprepared, they risk damage to lab equipment and more importantly injury to themselves and others. Though preparation is clearly important, one question repeatedly raised by students is why this requires an assignment. Pondering this, we have identified two core objectives for the pre-lab period and tailored assignments around these goals:

1. Students should be knowledgeable of both the theory and execution of the experiment prior to entering the lab.
2. The assignments themselves should be of pedagogical value rather than being punitive or a base assessment.

The first objective is intuitive and obvious; students need to know the means to complete their tasks in lab, and a background in the theory of the experiment is needed to fully glean the import of the steps they undertake and data they gather. While this describes the content of the assignment, the second objective shapes the delivery mechanism. A well-prepared manual can provide the needed introduction to both theory and procedure, but as a stand-alone reading assignment we have found student compliance low and preparation to complete in-lab objectives insufficient. Unlike other courses that have turned to individual quiz assignments to ensure preparation, we have found a blend of assignments can better increase both student compliance and understanding.

The first material we created was a video introduction to the experimental setups. The material covered included safety precautions, basic theory, and operation details that are difficult to communicate in other media, such as the location and manipulation of switches and valves. Videos are kept short, under 5 minutes per experiment, to maintain attention span while also adding a minimal workload. When posted as an optional aide, during the first year of availability students (n=194) averaged 11.5 views per-person. With only 5 assigned labs per student, this shows students are not only willing to watch but repeatedly re-watch videos to prepare for their lab. Observationally, instructors and lab managers reported seeing an increased readiness in how to perform the experiments, but little difference in the knowledge of what tasks need be completed and the steps to do so.

Yet initial design of an assignment focused on experimental procedure presented difficulties. The option to assess students at the start of a lab period would not allow time for correction and preparation and would need to rely on the import of a pre-lab grade to drive students to prepare. If quizzed prior to the lab period, students would be able to search out only the relevant procedural portions and still fail to understand the complete workflow. To tackle this problem, we realized that one of the key drivers to increasing preparedness had been student safety, and it was here we found our solution. A common industrial practice, supported in the United States by the Occupational Safety and Health Administration (OSHA), is the completion of a Job Hazard Analysis (JHA, also Job Safety Analysis or JSA) prior to the execution of any new, complex job. Intrinsically, a JHA is a worthwhile task to train students on as it will be a task seen in internships, co-ops, and many industrial- or research-based engineering careers. To complete a JHA, a job must be broken into its constituent tasks; in context of a lab experiment, this means that students must identify and describe in their own words each significant action they will undertake during experimentation. While often not in complete sentences, this assignment is akin to having students write out the experimental procedure prior to entering the lab. Students thus must read, comprehend, and explain each operation. Furthering the need for students to fully understand the impacts of their actions, an appraisal of any safety concerns and possible controls must be performed for each basic task. For example, should a task be to charge a reactor, the possibilities for changes in pressure, temperature, or hazardous reactive products must be considered. To create expectations as to what will result from each action, students are compelled to understand the theory behind each experiment before they perform it. An alternative task to a JHA may be to require students to complete the Theory and Procedure portions of their reports prior to entering lab. However, this puts a higher obligation on the students to produce a polished written work-product and opens the door to regurgitated procedural instructions that are not individually analyzed and understood. Such a method also does not benefit from forcing students to consider any hazards they may be exposed to, or generate, in the lab.

The JHA form we have developed is seen below in Figure 5. The basic format is able to be expanded as needed for more involved or hazardous experiments. The final portion of the form is a checklist to be filled out at the end of the lab period. A checklist not only helps ensure the lab is left in a safe condition, but also implicitly requires students to have the JHA form while they perform the experiment. The pre-lab assignment not only is preparatory but can guide students during the experiment as well. Instructors and Teaching Assistants have seen a sharp drop in the number of groups entering lab without a clear sense of the tasks required of them and how to begin the experiment. The lab period is more efficiently utilized, and students better positioned to comprehend the meaning of their actions and implications of their results. Yet quantitative assessment of student preparedness has proven challenging. Teaching assistants are asked to assign a score from 0 to 8 gauging student readiness to perform the experiment. Comparing the semesters before ($n = 135$) and after ($n = 120$) the introduction of the JHA, there was a statistically significant ($\alpha = .05$, $p = .0073$) drop in mean preparedness from 7.92 ± 0.05 to 7.79 ± 0.08. One immediate concern of note is the consistently high mean values; there is little room to statistically improve from a 7.92/8 mean despite observational reports of inadequate readiness. The decrease in score after the JSA was introduced thus likely is explained by TA's having a better framework to assess student understanding. As the technical components of all experiments have remained consistent over the study period, a change in final outcome, that is the technical score of the lab report, would likely be due to either population variability or a change in preparedness. A comparison of the technical scores on the completed reports do show significant improvement following the implementation of the JHA, with average scores increasing from 49.5 to 53.2 ($p = 5.5*10^{-7}$).

Georgia Tech Chemical & Biomolecular Engineering	Job Safety Analysis (JSA)	Date of Lab:

Experiment:

Group Number:	Group Members:

Personal Protective Equipment

☐ safety glasses ☐ lab coat ☐ closed-toe shoes ☐ nitrile gloves

☐ insulated gloves ☐ hearing protection ☐ other ____________ ☐ other____________

	Step	Potential Hazards	Controls
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

Prelab Approval Sign-off: ______________________ ☐ Accepted ☐ Minor Revision Required ☐ Insufficient ☐ All members present ____ / 8 pts

Completion Checklist:

☐ ☐ Equipment shut down ☐ ☐ Solid/aqueous waste properly disposed of

☐ ☐ Unused materials properly stored ☐ ☐ Data transferred off of lab computer

☐ ☐ Proper TA notified and area checked: ____________________ ____________________

Figure 5. Example JHA form completed prior to conducting experiment.

Conclusions

The inclusion of ever more content into time-constrained laboratory classes may initially concern most instructors. However, by implementing the methods outlined here, we have found it possible to satisfy additional ABET learning objectives while fostering student growth in a variety of professional skills. With an in-house communications program, students are able to strengthen their communication skills by integrating them into their technical assignments in both written and oral forms. A strong focus on lab preparation and safety also helps students gain industrially relevant experience while applying process safety principles. Moving forward, we look to find improved methods of quantifying student growth and the instructional effectiveness of our teaching approaches.

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