

A Writing in the Disciplines Approach to Technical Report Writing in Chemical Engineering Laboratory Courses

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Abstract

Purpose. While many engineering programs require technical writing courses, students tend to view writing as unrelated to their technical work in engineering. Faculty commonly complain about a lack of progress in student writing of technical reports in laboratories. Faculty also have few opportunities to learn about effective writing instruction. This paper presents a study that integrated a writing-in-the-disciplines approach into chemical engineering undergraduate laboratory courses. Specifically, we investigated whether students would transfer what they learned from one short technical report to another. Our approach involved component submission, providing feedback, and requiring revision on a first short technical report, followed by a second short technical report that involved only component submission.

Methodology. Unlike many programs that offer one or two 3-credit laboratory courses, our program—at a Hispanic-serving research university in the Southwestern United States—offers four 1-credit laboratory courses, spanning the junior and senior years. We revised the writing process in three of the lab courses. Students complete two short technical reports one component at a time; on the first, they received feedback and revised their work.

To assess the impact of these changes, we compared the total scores from the first and second reports that instructors provided using rubrics. The rubrics evaluated both conceptual knowledge and writing quality resulting in composite scores that reflect overall report quality. We conducted t-tests to evaluate whether students transferred their understanding from the first short report, on which they received intensive feedback, to the second, on which they did not.

To understand faculty perceptions related to writing and the feasibility of our approach, we interviewed faculty about their experiences.

Results and conclusions. We found that the overall quality of reports improved from the first to second report, $t(48) = 3.19, p = .003$ in the Spring junior lab and $t(54) = 3.76, p = .0004$ in the Fall senior lab. Interviews with faculty highlight that while students initially disliked the emphasis on writing, across semesters they came to view it as beneficial. We see this as tied to using variants of a consistent feedback-and-revision approach across multiple semesters.

Implications. This study reinforces past research showing the benefits of writing in the disciplines approaches. We share faculty insights about managing the feedback workload through differentiated rubrics and providing oral feedback, component submission and peer review.

Introduction

Technical writing is an essential communication skill for engineers [1-4]. Many engineering programs require technical writing courses; however, engineering professionals are often categorized as lacking effective communication skills [1, 5]. Students tend to view writing as

unrelated to their technical work in engineering or are reluctant or unable to identify technical issues or grammar errors in their writing [6].

In order to support students to develop effective communication skills, laboratory courses, which generally require students to communicate their results in the form of technical reports, are an ideal place for engineering faculty to teach writing. However, faculty commonly complain about a lack of progress in student writing of technical reports, and they face several challenges in remedying this situation. Large class enrollments and limited lecture time make it challenging for faculty to embed more writing in their curriculum. Many faculty are reluctant to implement writing instruction within their courses because they view themselves as content experts, not writing specialists [1]. Faculty need guidance on how to craft effective writing assignments, but there are few opportunities for them to learn about these strategies. Faculty tend to perceive that writing consultants and workshops are not effective [7].

In this paper, we build on past research on improving engineering student writing, particularly focused on feasible approaches to feedback and revision as supports for learning both content and writing conventions in chemical engineering laboratory courses.

Background

Teaching writing in engineering can help orient students to the discipline and help them master course content [8-10]. We draw upon research on effective writing instruction, especially related to two common research-based approaches, *writing in the disciplines* (WID) and *writing across the curriculum* (WAC), and research showing the value of feedback and revision for improving writing and supporting technical content learning.

Writing in the disciplines (WID) supports learning to write

Writing in the disciplines (WID)—also described as *learning-to-write*—refers to a distinctive approach to teaching students how to write in specific disciplines [11]. While technical writing courses taught in English department can focus on generalized technical writing, each discipline has its own writing conventions. For instance, technical communications in business and science are quite different from one another, and even within engineering, a report for a journal is different from an internal technical memo used in industry. WID focuses on supporting students to learn discipline-specific communication [11]. In such documents, the accuracy of the technical content and the clarity of the writing are emphasized.

To support this kind of development, WID typically emphasizes interactive dialogue between the students and faculty member. This helps students develop their identity and disciplinary understanding through purposeful discipline-specific writing [12]. The process of crafting a disciplinary manuscript parallels engineering design process, as both are iterative, require many decisions, and neither has a single correct answer [13].

In engineering laboratory courses, WID encourages faculty to scaffold student writing using discipline-specific writing assignments [14]. This works best when the assignments feel authentic to students, such that they see a purpose in communicating the findings of their research [15]. For instance, in the context of a design course, students were presented with ill-

structured, real-world problems such as from Engineers Without Borders. They applied previously learned engineering knowledge to analyze and develop solution for design problems and presented these solutions in various forms (technical lab report, proposal, and oral presentations). The authenticity of the problem engaged students to address a specific audience with a clear objective in mind, and students viewed the instructor only as a secondary audience. In the absence of such authenticity—a common issue in technical laboratory courses where the same experiment is typically recycled year after year, albeit with variants—it can be particularly difficult for students to write to an external audience. To aid in this effort, WID increasingly involves collaboration between engineering faculty and composition faculty [8].

Writing across the curriculum (WAC) supports conceptual learning

Writing across the curriculum (WAC)—also described as *writing-to-learn*—refers to an integrative approach of emphasizing written communication as a form a learning across the entire curriculum [16]. In this approach, the emphasis is not on discipline-specific styles of writing or the mechanics of writing, but rather, to help students make sense of and organize disciplinary content, generally in ways that connect to students' experiences and enable them to receive feedback on their understanding [17]. Thus, writing in engineering courses can be a powerful pedagogical and assessment tool to engage students in transforming their understanding [13]. For instance, Elder and Champine [18] conducted a mixed-methods study to examine the impact of using writing-to-learn assignments for students in undergraduate mathematics courses with a high failure rate. The writing assignments were modified or created to address the specific learning objectives of a math course for majors and a math class for non-majors. Students in the experimental group completed a problem-solving assignment and an additional writing assignment on the same topic. Students in the control group completed a problem-solving assignment and additional problems. The writing assignment helped students understand the mathematical processes, rather than taking a plug-and-chug approach that those who completed additional problems tended to use.

WAC has been widely used in engineering laboratory courses. Written assignments in laboratory courses range from predictions, exit tickets and reflective assignments through drafts of technical reports. For example, Walk [19] implemented a weekly low-stakes writing assignment in an undergraduate electric power and machines laboratory course. These writing assignments were specific to the topics each week and students completed these at the end of each lab.

However, adding such writing assignments can increase the grading burden for faculty. To mitigate this issue, faculty can simplify the writing tasks, using prompts that involve explaining a specific concept, problem, or involve defending a choice, and streamline and standardize grading by adapting existing rubrics [20]. Faculty have also observed that WAC assignments may ultimately reduce the grading burden of final versions, which are higher quality and easier to grade [19].

Feedback and revision support learning

A fundamental observation from research on learning is that students can benefit from feedback and revision [21-23]. Teaching writing in laboratory courses through feedback and revision can jointly improve student learning and writing [2, 3, 5, 24, 25]. However, when instructors provide

feedback but do not require revision, any feedback is rendered inert, as students commonly do not review the feedback deeply or may not understand how it applies to future assignments. Even when rubrics and templates are provided, without revision, such feedback is not useful for students [2]. Providing guidelines or templates, requiring fewer total reports, and allowing time for feedback and revision can support improved understanding and writing [2].

Furthermore, not all feedback is effective [26]. It is common practice for faculty "bleed all over" student writing, marking many different types of errors [2]. Research on different types of feedback has clarified that this approach is not effective [27]. In order for feedback to be effective, students must understand it and know how to apply it [21, 22]. This suggests that a less-is-more approach may be desirable, especially where instructors model a correction and request that students themselves make the remaining corrections.

In addition to asking students to revise based on instructor feedback, engaging in peer review can be beneficial, especially for the peer-reviewer [6]. Likewise, written and oral feedback from a peer learning facilitator or graduate teaching assistant can help students learn [3], even with difficult writing tasks such as argumentation and synthesis [23].

In the current study, we consider different variants of feedback-and-revision, as implemented by three different engineering faculty in laboratory courses.

Methodology

Study design & research questions

In this study, we developed and evaluated the impact of a collaborative approach to supporting students to learn technical writing in engineering laboratory courses. We employed design-based research [28-30], an iterative approach to testing designs for learning and building learning theory. Typically, these theories are *bricolage theories*, meaning they are constructed from existing research but tailored for the particular study context. In this study, we tested the theory that providing clear guidance and feedback, component submission, and opportunities for revision, and in some cases, reflection, would support improved technical writing and conceptual understanding. We specifically consider the feasibility of our design for all members of the instructional team (undergraduate peer learning facilitators (PLFs), graduate teaching assistants (GTAs), an embedded writing instructor, engineering faculty of various ranks and an engineering laboratory director). The writing instructor serves several roles, working closely with both faculty and students. With course instructors, she develops rubrics and writing prompts for assignments. She assists with grading student work, including working with students to improve their drafts. In this study, we report on iterations in three courses; in each iteration, this theory was instantiated into the course in different ways. This jointly provides insight for faculty who desire to adapt our approach, and allows us to compare the variants in terms of opportunities for learning and workload burden. We address the following research questions in this study:

1. What do instructional team members see as the barriers to and affordances of incorporating feedback and revision into technical writing in chemical engineering laboratory courses?

2. How might incorporating a writing instructor and variants of component submission, feedback, and revision support students to improve in overall quality of technical report writing in chemical engineering laboratory courses?

Participants, setting, & materials

This research was conducted at a Hispanic-serving, research-intensive university in the Southwestern United States in an undergraduate chemical engineering program. The program has been making major curricular changes, and this afforded the opportunity to address a common pain point for faculty: despite providing copious feedback, student writing was not improving.

Students complete four 1-credit laboratory courses in their junior and senior years. In this study, we report on changes to three of these courses. Each course included three complex experiments. To make our changes, we reduced this to two complex experiments, carefully considering which experiment to omit based on student feedback and outcomes. We then introduced variants of feedback and revision related to two short technical reports. Each lab includes a prelab with a job safety analysis (JSA) and experiment planning, as required by ABET. Students complete the experiment as a team and turn in a draft of their methods during the experiment. Following the experiment, they have some form of postlab experience, which typically focuses on their analysis and interpretation, including the quality and accuracy of calculations, figures, tables, captions, and inferences. Each student is responsible for writing their own short technical report. In past, students turned in the full report, but in our revised approach, they turn in components, drafting different sections each week. This jointly makes grading more manageable for faculty and writing more manageable for students, allowing them to focus on and learn specific expectations for each section. Ultimately, they have fewer revisions to make because, after receiving feedback on one section, they make fewer errors on the next. Students received intensive feedback on their first technical report. On the second, while they could seek feedback and make revisions, this was not required.

The embedded writing instructor iteratively designed rubrics and instructions with the engineering faculty (Figure 1, Appendix). Drawing on her experience teaching technical writing courses in the English department, she drafted and adapted rubrics, then sought feedback from engineering faculty. Engineering faculty provided criteria for technical content relevant to the particular experiment, such as the accuracy of methods of analysis and equations used, results within one standard deviation, and accuracy of their predictions based on modeling. Engineering faculty also helped the writing instructor understand technical writing expectations and conventions in chemical engineering, and she helped them understand conventions from WAC/WID approaches. Each rubric included criteria related to both writing mechanics and technical content.

The first course to be implemented with the revised approach was the Fall senior lab. The writing instructor adapted rubrics and instructions with faculty who taught the Spring junior and senior lab courses.

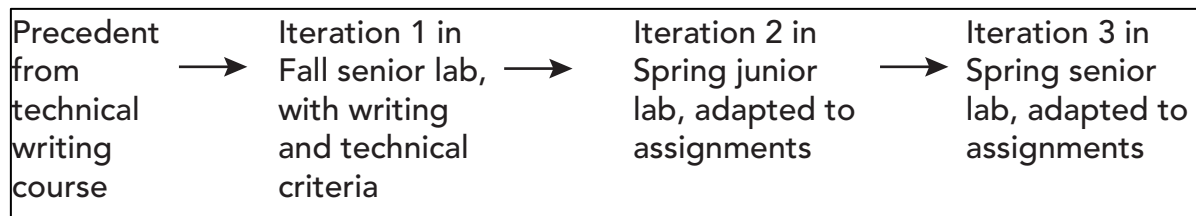


Figure 1. Iterative co-design of rubrics and assignment instructions

Spring junior lab. The Spring junior lab is taught by a teaching-intensive engineering faculty member supported by the embedded writing instructor, the chemical engineering laboratory manager, and undergraduate peer learning facilitators (PLFs). In this course, the experiments focus on transport phenomena. Students conduct experiments related to friction in fittings, efflux from a tank, and conductive heat transfer. They investigate pressure drop in a piping system, determine thermal properties of various types of wooden blocks with COMSOL modeling and determine flow properties through different pipe segments.

Students complete a JSA and receive oral and written feedback on their prelab to prepare them for completing the experiment (Figure 2, Appendix 1). As part of the assignment instructions, the engineering faculty member provided a template for a short technical report to scaffold students' writing. Following the experiment, students received written feedback from the PLFs on their post-lab reports. Individually, students submitted draft short reports containing only the results and discussion section; PLFs provided feedback on these in writing. As teams, the students met with the embedded writing instructor and the engineering faculty member to get oral feedback. They then revised their individual reports, including adding other sections.

Fall senior lab. The Fall senior lab is instructed by an associate professor supported by the embedded writing instructor, the chemical engineering laboratory manager, and PLFs. In this course, the experiments focus on heat and mass transfer and unit operations. Experiments include heat exchangers, wetted wall columns, and distillation columns, topics students had learned about in preceding courses.

Students receive written and oral from the engineering faculty member on pre-lab questions before conducting the experiment (Figure 2, Appendix 2). PLFs provide feedback on their post-lab analysis. Based on this, students individually write draft short technical reports. While the engineering faculty member provides feedback on the technical content, students provide feedback to one another on their writing through a scaffolded peer review process co-designed by the engineering faculty and writing instructor. Students first read their partner's draft straight through without correcting or editing, focusing on content, clarity, and coherence. Then, using a rubric, students provide feedback on areas for improvement, as well as on where the draft is effective. In addition to submitting this written feedback, students also reflect on the process of peer review, noting what they learned and will apply to their own writing. Following this, students have opportunities to meet with the engineering faculty and/or writing instructor for additional oral feedback. Along with revising, they submit a memo detailing changes made.

Spring senior lab. The Spring senior lab is co-instructed by the department chair, a GTA, and the embedded writing instructor. In this course, students perform two laboratory experiments that

allow them to apply knowledge learned in previous semesters on chemical kinematics (selective hydrogenation of acetylene in acetylene—ethylene mixtures) and process control (comparing a heuristic-based approach with statistically designed experiments to tune a liquid level controller). In the first, students develop a model for the reaction, test the model by doing experiments, then use the model to optimize parameters for an industrial process. This experiment teaches students the importance of planning activities so meaningful data can be collected in limited time, testing their hypothesized model to validate it, and then using appropriate mathematical tools to perform optimization. In the second experiment students tune a control system using a heuristic approach. They use a statistical package to perform a three factor central composite design to decide which experiments to run so that adequate data can be obtained. They apply the tools of Response Surface Methods (RSM) to determine the best operating conditions for the level controller and test if the statistically designed experiment yields better control than the heuristic parameters. The experiment gives them an opportunity to practice what they learned in an applied statistics class during the previous semester, as well as giving them a chance to learn how an industrial process control system functions.

In the oral pre-lab, students first demonstrate that they understand and have adequately planned their experiment (Figure 2, Appendix 3). They then write the introduction. Each component assignment is graded by the writing instructor using a rubric and in consultation with the engineering instructors. As students get this feedback, they may opt to seek additional feedback and/or revise component sections (and most students take advantage of this opportunity). Students conduct the experiment over two weeks, with the methods section due at the beginning of their experiment. In the oral postlab session, the writing and engineering instructors provide feedback on their results and discussion. Students then individually write the results section, then the discussion & conclusions section the following week. Students then present an oral report and get feedback from both the writing and engineering instructors. They then submit a final short report, incorporating the revisions they have made to component sections.

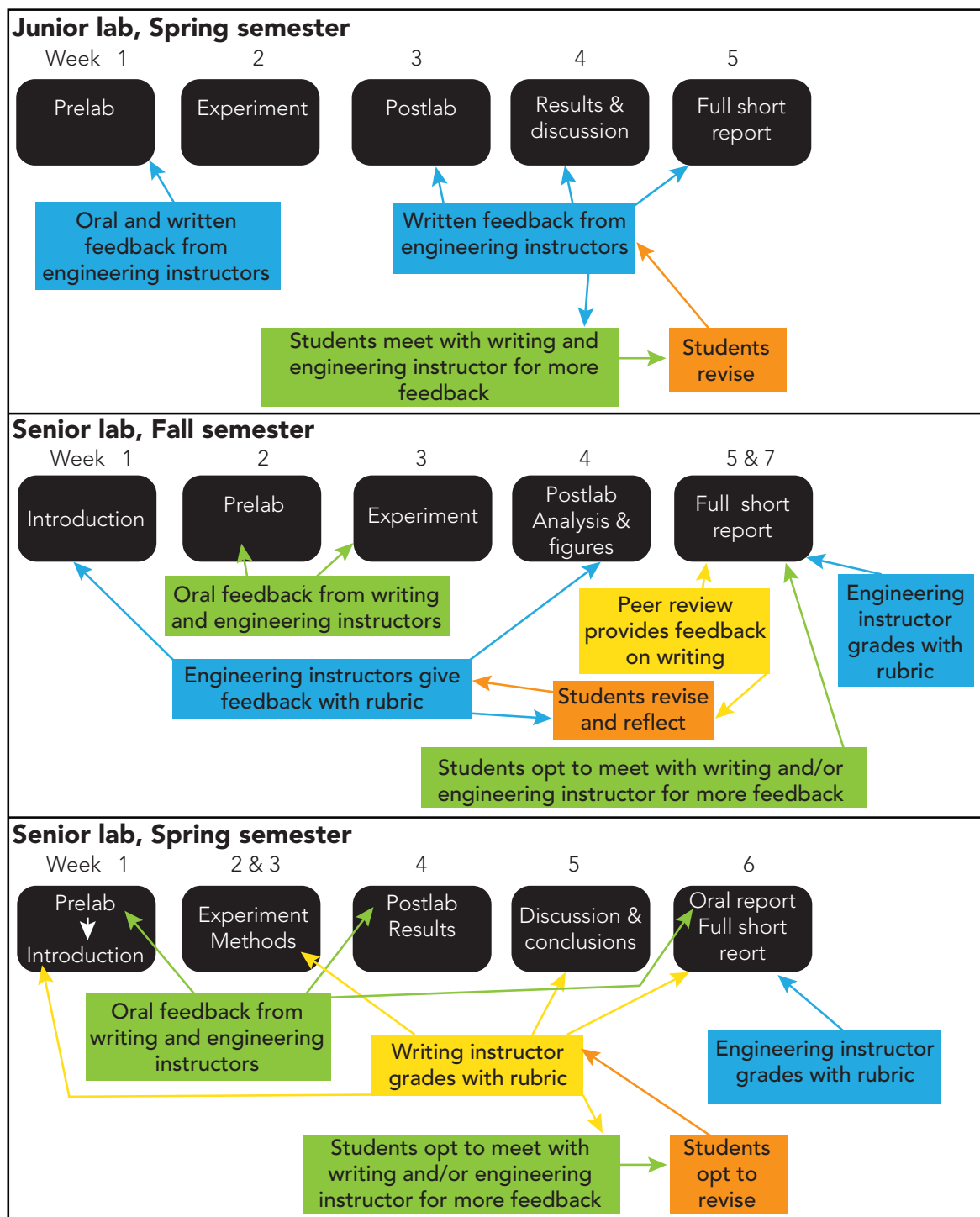


Figure 2. Overview of the component submission, feedback, and, revision process across three chemical engineering laboratory courses. *Key: Yellow = feedback from writing instructor or feedback focused on writing; blue = feedback from engineering instructors (faculty, undergraduate peer learning facilitators, and/or graduate teaching assistants); green = combined feedback from both engineering instructors and the embedded writing instructor.*

Data collection and analysis

To evaluate the impact of the changes across the three courses, we gathered the rubric-based scores on the two short technical reports in each course. We used total scores as assigned by instructors using the rubrics. Thus, the scores are composite, but typically reflected similar categories (see Appendix), including writing quality and conceptual understanding. To make the scores easier to compare, we calculated percentages for each.

We calculated descriptive statistics and conducted t-tests to compare student performance on the first technical report—on which they received much more feedback—to the second technical report—on which they receive less feedback. We hypothesized that if students were learning to write as engineers, they should transfer their understanding from the first to the second technical report.

We interviewed faculty about their experiences at multiple time points. Interviews focused on multiple aspects of curricular change ongoing in the department. We transcribed these and selected comments focusing on changes to technical writing.

Results and discussion

We organize our results by research question. The first question investigated faculty perceptions of the writing approach.

Faculty buy in, opportunities to learn to teach writing, and gaining student buy in

Interviews with faculty suggest that they supported the changes to teaching writing because they perceived that these changes would improve students' writing competency for their future careers. One faculty member stated that writing is like a "symptom" because it is challenging for students to become good writers. Incorporating the embedded writing instructor into laboratory courses enabled faculty to be more involved with students' writing process. Faculty members felt that the embedded writing instructor provided students with effective feedback, which supported students to make revisions to their short technical reports.

By interacting with the embedded writing instructor, faculty members not only learned about and implemented different approaches to teaching writing, but felt more efficacious in their teaching. For example, one faculty member stated that:

In my own teaching, I've always recognized writing as important, but I didn't really know how to teach it better. And then, just by interactions with [the writing instructor] and some of the readings that I've done on my own, I've also incorporated a lot of writing even in other parts of the lab aside from the peer review and revision. [...] And then also, not just writing for writing' sake, but writing for them to learn better as well.

As experts in their disciplines, the faculty members cited that their preparation did not include how to teach, and especially, not how to teach writing. They were experts in content knowledge and skills, but teaching writing requires a different set of skills. Some faculty pointed out that it has been challenging to engage a large class effectively, but by finding resources on campus,

specifically, a writing instructor, they also learned why a general technical writing course taught in English might be very well taught, yet insufficient. For example, one faculty member stated that:

How do we interact with this large class and still make it effective so people are learning from those methods that somebody has developed? It forced us to find resources on our campus. We wouldn't have known that the English department does a good job, but they are not successful because they don't know what writing we do. We can sit here and point fingers and say, "English, they do a terrible job of teaching technical writing," but that's not true. They do a good job. It's just that they're teaching different things.

As engineering faculty have continued to work with the embedded writing instructor, they have had opportunities to learn and are able to present a much clearer sense that writing is a core skill for engineers; this integrated approach is critical if students are to come to understand that engineers are writers [31]. As the Spring junior course instructor explained,

A shared rubric for writing and technical content ensured there was no disconnect between the two areas and saved both instructors time. The incorporation of a writing instructor to focus on the report mechanics allowed the engineering instructor to spend more time with students on technical content without compromising writing quality.

Ultimately, both the engineering and writing instructors committed substantial time to the first iteration, but anticipate an overall reduction in time in future iterations, as the development effort is complete. They are optimistic that as students gain skills from one course, they will transfer these to the next.

Faculty recognized that these changes would need to be framed to gain student buy in.

Spring junior lab. For students in the Spring junior course, this was their first encounter with this approach to feedback and revision. The instructor explained that a writing instructor was embedded as part of the course to help with writing style and effective written communication of the analysis on each experiment. She explained to the students that they would have time to work on improving their writing, not just for the same experiment, but a different one as they work through two rounds of short reports. Most students earned low scores during the revision phase of the first short report and some commented "Instructors should not grade drafts so hard." By the second round, there was a noticeable appreciation for the meaning of a draft report as "almost ready, just minor revisions and editing." Students arrived prepared with hard copies or laptops to feedback sessions with the engineering and writing instructors; they were eager, especially in the second round of short reports, to report on what they improved from the first round. Additionally, some students made revisions prior to the session in anticipation of more feedback.

Fall senior lab. The instructor of the Fall senior laboratory course explained that she worked closely with the writing instructor to frame the writing process for students. Part of this involved referencing the ABET student outcomes as evidence that engineering involves a broader skillset than just the technical, but she also made a persuasive argument that "I have good news and good

news! You only need to do 2 experiments this semester. You will become a better writer." She explained her motivation for making changes and prepared students so they would know what to expect (Figure 3). To frame the peer review process, which is typically new for students in chemical engineering classes, the Fall senior laboratory course instructor shared an example from her own research (Figure 4), which highlighted that revision is the norm even for experts.

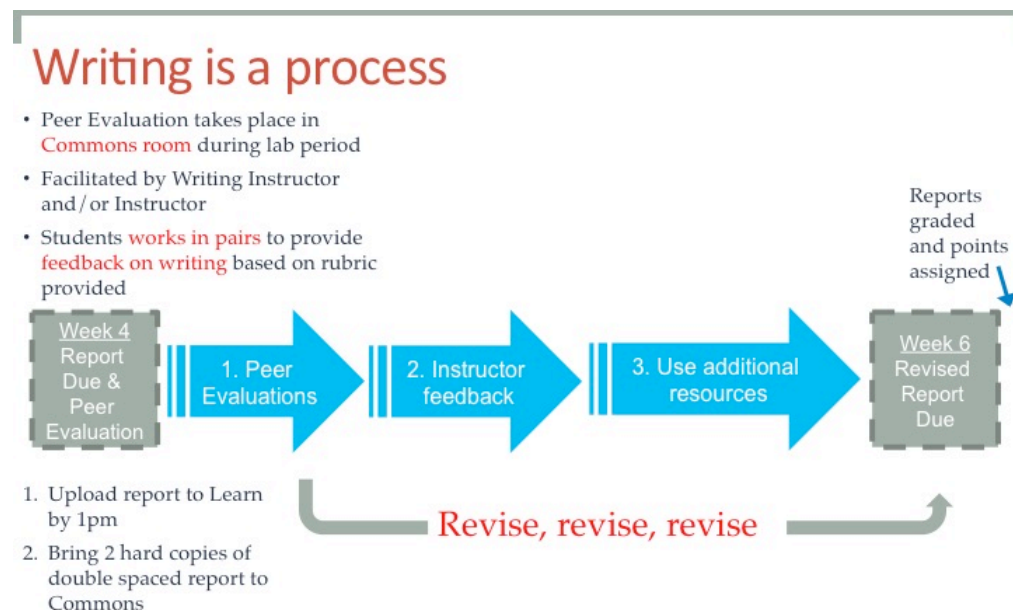


Figure 3. Sample slide the engineering instructor for the Fall senior laboratory course used to frame students' expectations about the feedback and revision process

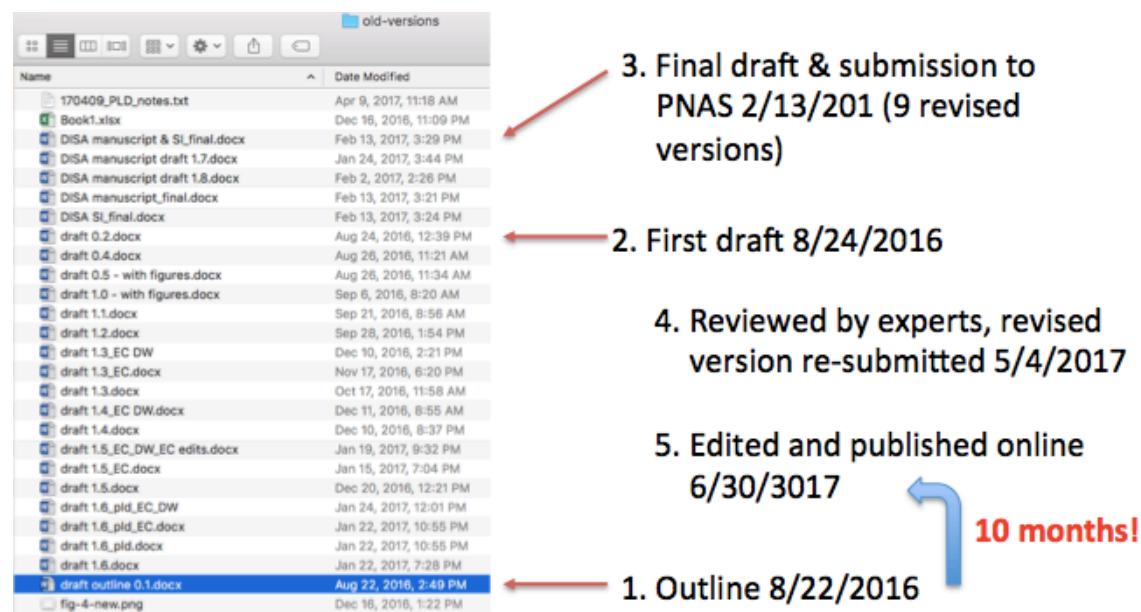


Figure 4. Sample slide the engineering instructor for the Fall senior laboratory course used to situate peer as something even experienced engineers must do

As a result of adequately framing students' expectations, the Fall senior course instructor observed that she gained buy-in from students:

So overall, we were very cognizant that we should inform students as to why and how we do things and get their buy in. The response to the peer review and revision process (based on reflections and memos) has been overwhelmingly positive.

She also noted that students asked "many, many more questions" as part of peer review, "about their own writing or technical writing in general, verb tense (why passive voice?), first vs. 3rd person (why not first person), etc." This suggests that the process of peer review helps them notice many of the disciplinary conventions they need to learn.

Spring senior lab. Students in the Spring senior course had just completed the Fall course. The engineering and writing instructors explained that they were going to teach them how an effective technical communication is prepared. They provided a template used by the American Chemical Society journal *Applied Materials and Interfaces*, a format that stresses brevity with two columns that force students to use their figures and tables more effectively. The final product looks very similar to a manuscript that would be submitted to a journal. This was appealing to the seniors since many aspire to go to graduate school, so having this skill would make them more effective in their professional careers.

The engineering instructor explained that in his first job as a chemical engineer, he learned how to write technical reports because his supervisor did extensive edits with red ink. He told students they could bypass that step by learning better writing in this senior lab, one of the last technical courses in their curriculum. They explained the component submission approach (see figure 2), telling students that each week—concurrent to conducting the experiments and analyzing their data—they would do some writing, typically less than a page, and at the end of 6 weeks they would have a complete report. Students appreciated that each week's writing assignment was short and based entirely on what they did in the lab during that week. At the end of the course, seniors attend a farewell lunch, where we survey their experiences in our program. Students were uniformly supportive of our efforts to help them become better at written communication.

Impact on students

To evaluate the impact on students, we compared total scores assigned, using rubrics, on the final versions of the first and second short report in each course (Figure 5).

In the Spring junior lab, students scored higher on the second short technical report ($M = 82.7\%$, $SD = 7.9\%$) than they did on the first short technical report ($M = 79.3\%$, $SD = 8.3\%$) and this difference was significant, $t(48) = 3.19$, $p = .003$.

In the Fall senior lab, students scored higher on the second short technical report ($M = 87.7\%$, $SD = 14.3\%$) than they did on the first short technical report ($M = 80.4\%$, $SD = 19.1\%$) and this difference was significant, $t(54) = 3.76$, $p = .0004$.

In the Spring senior lab, students scored higher on the second short technical report ($M = 84.2\%$, $SD = 12.0\%$) than they did on the first short technical report ($M = 81.4\%$, $SD = 20.3\%$) but this difference was not significant, $t(55) = 1.15$, $p = .256$.

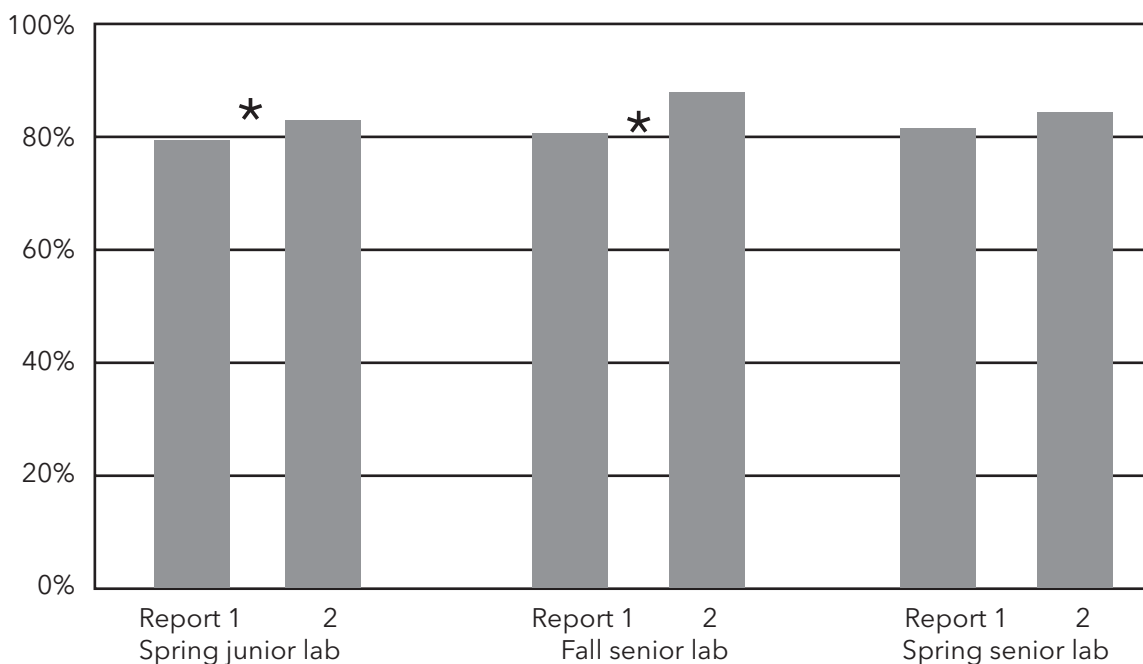


Figure 5. Scores assigned to the final versions of the first and second short technical reports in each course. Students in the junior course are in a different cohort than in the senior courses. * indicates significant difference from first to second report.

Across all three courses, students made gains from the first to the second technical reports, and in two courses, this gain was significant. Keeping in mind that the students from the junior Spring lab were not the same students as in the senior labs, these data are longitudinal only for the senior labs. It is notable that these gains were observed despite the fact that students received far less feedback on their second short technical reports.

Conclusions, limitations, and implications

In this study, we detailed three variants of component submission paired with feedback and revision across three chemical engineering laboratory courses. Although they only received intensive feedback on their first short technical report, students earned higher scores on their second short technical report. This suggests that they transferred what they learned about technical writing from the first to second technical reports.

One strength of our study is that the same general approach—component submission, feedback, revision—was implemented in different ways, yet still supported improved technical report quality. This suggests that there is not just one right way to implement. Our analysis of faculty perceptions suggests that they worked to frame the importance of writing and revising to students. While this was not a key feature of our original theory, we suspect that successful

implementation may hinge on this, and would encourage any faculty interested in replicating to consider how to frame the importance of writing and revision to students.

It is important to note that our setting is different from others, in that students completed two complex experiments per semester. We have thus far not noticed any negative impact on students' conceptual understanding as a result of this change. Yet, we recognize that other programs may include many experiments per semester, with a lab report due for each experiment. Our findings align to research that teaching writing in the disciplines can improve both conceptual understanding and writing quality [8-10], suggesting that teaching writing does not come at the expense of content. Research also suggests that reducing the number of lab reports may ultimately lead to more learning and higher quality writing [2]. Others have argued that requiring revision of just a first lab report can be beneficial [32], and our findings back this assertion.

That the increases in the Spring senior lab from the first to the second technical report were not significant may be attributed to several possible causes. It is possible that there was a ceiling effect, with higher scores on the first report limiting potential growth or that our approach can only support so much growth, and further practice results in diminishing returns. It is also possible that the variant used in this particular course was less effective. Compared to the other variants, this one did not require revision, leaving it in the hands of the students. As graduating seniors, we might expect that they would understand the benefit and take advantage of this opportunity, but we also acknowledge that graduating seniors have many competing interests, and some may not have viewed revision as worth their time. Future work will investigate this further, especially to ascertain if there is a benefit longitudinally.

One limitation to our study is tied to the data we used. First, we analyzed total scores rather than scores from specific areas on the rubrics. As such, our analysis cannot distinguish between improved writing quality and improved conceptual understanding. Future work using a more fine-grained approach will provide better information about areas for improvement. Second, the scores were provided by faculty without a measure of their reliability. However, because the embedded writing instructor assisted with all aspects of the rubric and assignment development, we see this as a minor concern and as reflecting pedagogical practice. However, our future research will involve estimates of reliability across instructors. In this process, we will also review and revise rubrics.

One way we have made our approach feasible is to work closely with PLFs and GTAs. This approach, employed by others for similar reasons [33], requires having well-designed rubrics and some training for the PLFs and GTAs. As we have located additional campus resources, we have found support for this training from our faculty development office.

Based on the success of the first iterations in three laboratory courses, we are expanding and formalizing our approach. Recent changes to our university's core curriculum have opened the opportunity to remove the 3-credit technical writing elective from students' program's of study; we will replace it by integrating technical writing with the experiments. Our ongoing research will investigate how best to integrate these two courses such that students get consistent feedback, recognize technical writing as a core competency for engineers, and learn as a result of component assignments, effective feedback, and revision.

We also found that faculty framed students expectations about writing, including letting them know that students would improve and that revision was a normal part of engineering writing, even for experienced writers. This, paired with students seeing actual benefits on their writing, fostered student buy-in. Faculty plan to cite our success to date as they engage with students in future courses to further enhance their buy-in.

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Appendix 1. Rubric for Spring junior lab

Criteria	Description		
Content	9 to 10 points The report includes all the sections of a good short report. Each has an opening, body, and transition or closing paragraphs that clearly describe the researcher's problem, methods, experimental results, and the writer's conclusion about each major finding or objective.	7 to 8 points One or more components are missing.	0 to 6 points Needs major revisions.
Style	14 to 15 points The final short report successfully and persuasively employs plain style and offers a direct and engaging narrative. Sections are fluid and any repetitions appear necessary to the advancement of the narrative. Sources are included, cited appropriately, and included in the reference section. Most sources are not from course materials.	12 to 13 points The writing is convoluted and some of the meaning is lost, or references are not cited according to conventions.	0 to 11 points Needs major revisions.
Coherence	14 to 15 points The short report conveys the author's ideas effectively. Coherence includes such elements as clear and consistent sentence organization, and effective flow of ideas. Figures and are appropriately referred to in- text, displayed effectively, and advance the narrative. The captions and titles are descriptive and conform to reader expectations.	12 to 13 points The organization needs improvement to improve readability, or if a figure is included, it is not placed effectively in the document's layout, or the caption lacks adequate description	0 to 11 points Needs major revisions.
Purpose of Experiment, Procedure and Main Equations	9 to 10 points Clear statement of the scientific aim. Procedure contains enough information that is reproducible, necessary and relevant. Important equations are listed and briefly described.	7 to 8 points The purpose is not specific to the objectives and partly understood by author. Procedure is missing critical information required to reproduce the experiment, wordy in some sections and/or contains unnecessary information.	0 to 6 points Needs major revisions.
Key points	14 to 15 points Contains all figures and tables that support the major objectives. Contains no irrelevant or redundant data. Data processed correctly, logical and organized in a professionally formatted manner	12 to 13 points Missing critical data and/or contains irrelevant data. Data processed incorrectly in some places.	0 to 11 points Needs major revisions.
Technical Discussion	14 to 15 points Effectively uses data in key results to address the major objectives. The data is interpreted correctly and important graphical trends and values are highlighted as Supports with the theory, offering reasons for the deviations from literature values in terms of experimental conditions. Accounts for experimental error in measurements and their propagation to final calculated quantities and relates its significance when reporting results.	12 to 13 points The relationship between data and objectives are not clear and not always interpreted correctly. Theory is not tied sufficiently to support the objective.	0 to 11 points Needs major revisions.

Appendix 2. Rubric for Fall senior lab

The instructor used five levels to assign scores to each section:

- Correct = 100%
- Mostly correct = 75%
- Half correct = 75%
- Mostly incorrect = 25%
- Incorrect = 0%

Section	Description	Points possible
Length, format, aesthetics	The length should be 3-4 pages, including figures and tables, but excluding reference list or appendices. Font size should be no smaller than 11 pt., and margins should be no less than 0.75 in. Figures and tables also need to adhere to margin limits.	15
Cover Page	Does not count in page limit. Title of experiment, date of experiment, your name, the names of your lab partners. Title should be informative and reflects the content of the report.	15
Introduction and Objectives	One or two paragraphs that concisely state the objectives of the experiment	20
Procedures and Analysis	Brief (~ 0.5 page) summary of experimental procedure, nature of data obtained, and analysis used to provide results.	20
Results and Discussion	This is the meat of the report: 1.5-2 pages summarizing important results, explanation and interpretation of those results. Here it is appropriate to consider/discuss what the results mean, how they compare to theory, and how they relate to the objectives of the lab. Tabulated results and/or graphs are appropriate in this section, but you must be selective – they should be important and directly support your discussion. It is also very important comment on sources and magnitudes of error derived from the experiment and analysis, especially when this impacts the analysis or conclusions. Plotted or tabulated quantities derived from experimental data should generally have error bars (with the basis of those error bars noted), and/or comments in caption or the table/figure.	80
Conclusions and Recommendations	~0.5 page summarizing major conclusions or recommendations – this may relate to what you learned from the lab, or even to the equipment, procedure or analysis.	20
References	Does not count in page limit. Use ACS formats exist for references. For this class, use numbers in square brackets in the report, in the order of citation, and a References Cited list in numerical order in the References section. All references must be complete, and should be cited in the report.	10
Appendices and Calculations	Every Short Report for this class should be accompanied by a well-documented (and commented) spreadsheet that contains complete data and calculations covered in the report. See “What to Turn In” below. You may also want to have Appendices included as part of the report, which is fine. If included as part of the report, they should be numbered and properly titled and/or labeled. Figures and tables in Appendices normally need captions, just as in the report body.	20

Appendix 3. Rubrics for Spring senior lab

Results section (30 points)

Content	<i>9-10 points</i> The report includes all the components of a good results and discussion section. Each has an opening, body, and transition or closing paragraphs that clearly describe the experimental results and the writer's conclusion about each major finding.	<i>7-8 points</i> One or more components are missing.	<i>0-6 points</i> Needs major revisions.
Style	<i>9-10 points</i> The results and discussion section successfully and persuasively employs plain style and offers a direct and engaging narrative. The sections are fluid and any repetitions appear necessary to the advancement of the narrative. If references are included, they are cited appropriately.	<i>7-8 points</i> The writing is convoluted and some of the meaning is lost, <i>or</i> references are not cited according to conventions.	<i>0-6 points</i> Needs major revisions.
Coherence	<i>9-10 points</i> The section conveys the author's ideas effectively. Coherence includes such elements as clear and consistent sentence organization, and effective flow of ideas. If figures are included, they are appropriately referred to in-text and displayed effectively. The figure's captions are descriptive and conform to reader expectations for captions.	<i>7-8 points</i> The organization needs improvement to improve readability, <i>or</i> if a figure is included, it is not placed effectively in the document's layout, <i>or</i> the caption lacks adequate description.	<i>0-6 points</i> Needs major revisions.

Final short report (35 points)

Front Matter	<i>9 – 10 points</i> The report includes a descriptive title, team members and affiliations, date, and abstract. The abstract is approximately 100 words and concisely describes the problem, methods, results and main conclusions and recommendations.	<i>7 – 8 points</i> One or more components are missing.	<i>0 – 6 points</i> Needs major revisions.
Conclusion	<i>5 points</i> The conclusion summarizes the results and recommendations and if constraints are identified, suggests how the recommendations would be different.	<i>4 points</i> The analysis of results was performed incorrectly. Poor analysis led to incorrect conclusion(s).	<i>0 – 3 points</i> Needs major revisions.
Technical	<i>18 - 20 points</i> The technical portion of the report identifies and applies the correct equations/methods/analysis of the data, and presents the results in a coherent manner through tables, figures, graphs, etc. The design of experiment was planned and executed correctly. Error was propagated into results.	<i>16 - 17 points</i> The analysis of results was performed incorrectly. Poor analysis led to the wrong conclusion(s).	<i>0 - 15 points</i> Needs major revisions.