Qualitative Analysis of Student Experience in a Chemical Engineering Laboratory

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Qualitative Analysis of Student Experience in CHE Lab

Abstract

A multi-dimensional survey was created and administered to better understand the change in self-perceived and actual student abilities in a CHE laboratory course between two different student cohorts. One cohort experienced a traditional lab structure with a companion face-to-face lecture course (N=47), and the other cohort included pre-lab modules integrated with in-lab activities that served as intentional scaffolding for the student learning experience (N=18). The overall study was motivated by the desire to understand the impact curriculum revisions have on student experience and abilities, with the goal to improve the educational experience using evidence-based practices. The guiding research questions driving this facet of the study were:

What are the perceived objectives and perceived learning experiences of students in our CHE lab? To what extent do these experiences differ for students enrolled in the traditional course and the revised course?

Prior work explored student experiences in the laboratory by analyzing survey results from the Self-Assessment and Direct Skills Test [1-4]. These assessments contained primarily close-ended questions with some open-ended prompts. Distinct from prior work, the methodology for this effort followed the six phases for thematic analysis outlined by Braun and Clarke [5] and was applied using a phenomenological lens where the authors seek to describe different ways a group of people (chemical engineering students) understand a phenomenon (CHE laboratory course). Through this lens, the authors considered student responses to one open-ended question asked both at the beginning and at the end of the course. The question related to student expectations (before) and capabilities (after). Semantic and latent content were considered, and an inductive approach to identifying themes was applied. This work documents the process of applying those six phases, as well as the exploration of initial frameworks for coded thematic elements. We present codes and themes that emerged from the combined cohorts and discuss the extent to which those themes differ and evolve between the two cohorts. In support of these themes, we present "quantized" data visualized in a variety of ways as well as selected excerpts of student responses.

In addition to reporting on the research question itself, this paper will serve as a process guide for analysis of a small set of qualitative data in the context of chemical engineering education. The intent is to make thematic analysis more accessible for faculty who might otherwise not consider this approach in pedagogical work.

Introduction

Laboratory courses are often the first, and sometimes only, place where undergraduate Chemical Engineering students encounter real Chemical Engineering equipment and work in a large-scale laboratory environment. Beyond technical and sensory experience, capstone laboratory also affords students the ability to practice other critical skills, such as safety, experimental planning, troubleshooting, data analysis, written and oral communication, and teaming [6]. As it was perceived based on interactions with students in the laboratory course, the Chemical Engineering laboratory sequence at a small midwestern institution needed intentional scaffolding to encourage students to practice the various skills associated with the laboratory course.

Part of this curricular revision involved reviewing the structure of the introductory laboratory course. The original course had students completing a laboratory project that lasted an entire academic term while also attending a largely disconnected laboratory lecture course. The revised course converted the lecture course into a series of weekly topical modules, with in-laboratory activities being related to the pre-lab module that culminated in a final laboratory project. The first implementation of this used a control group of students who took the original class with laboratory lecture (N = 47), while an intervention group experienced the revised sequence with themed topical lessons and in-laboratory activities (N = 18). While the revised course did cover much of the same material as the original course, the revised course had specific activities designed around safety, identifying equipment, instrumentation, and items on flow diagrams. More details of the revised course can be found in previous work (removed for review) and in the section on laboratory course background.

To assess the impact of this change in the introductory laboratory class, student attitudes and skills were examined using a series of assessment tools. Some of these tools directly assessed student knowledge or abilities, while other instruments were used as a self-assessment where students could indicate their perceived knowledge and level of engagement. These instruments were given to students in both laboratory groups, who all belonged to the same graduating class, at the start and end of the first laboratory course in the sequence.

Prior work has focused on quantitative analysis of the self-assessments and direct assessments (our previous work, removed for review). While these survey tools contained primarily closed-ended questions (i.e., Likert scale, multiple choice, fill-in-the-blank), this work examines an open-ended prompt that had been previously unexamined. While analyzing quantitative data can yield information about what trends are occurring, reviewing qualitative data has the potential to show deeper perspectives and seek to explain how and why the trends exist. Indeed, analyzing qualitative responses on a survey item related to identifying appropriate chemical engineering principles governing the analysis of a heat exchanger led us to learn about missed opportunities to use technical terms and a tendency for students to misclassify “mass flow” as “mass transfer” (our previous work, removed for review). This approach will allow us to glean more information than simple numerical responses to the closed-ended questions. While it can be more difficult and time-consuming to parse through that much information, it was hoped that allowing students to explain their thought processes in open-ended questions would provide us a better understanding of the rich experiences and thought processes students engaged with during the laboratory course.

This work seeks to apply a qualitative analysis to an open-ended prompt found in the assessment instruments to provide further insight into how students developed through their first experience in the Chemical Engineering Laboratory curriculum. By conducting this analysis, we hope to provide answers to the following questions:

- *What are the perceived learning experiences of students in the chemical engineering laboratory introductory course?*
- *How do these student perceptions change over the duration of the first laboratory course?*

- *To what extent do these experiences differ for students enrolled in the traditional course and the revised course?*

By providing thematic analysis of these responses, we hope to glean further insight into the merits and limitations of both modes of class operation. While the quantitative analysis was useful for observing general shifts in knowledge, skills, and attitude, there is value in reading students' reflections that allow for context. Since student responses on Likert scale questions can be subjective and personal, we anticipate that qualitative analysis of the open-ended responses will expose the deeper thought processes of our students, allowing us to make more informed choices about our laboratory curriculum.

Laboratory Course Background

The capstone chemical engineering laboratory sequence begins with an introductory course (Lab I) where students learn about working in the laboratory and complete one experiment related to an assigned unit operation. The traditional offering of the course required a once-a-week, 50-minute lecture component where students were introduced to skills related to experimental planning, data analysis, and preparing reports. Students would then complete activities in the unit operations laboratory during once-a-week, four-hour sessions. Given scheduling constraints, it was possible for students to have not seen the week's laboratory material before going into the laboratory class that week. Major student deliverables included a final individual report and group presentation.

An updated Lab I course was proposed where lecture and laboratory content was more closely aligned. The lab lecture was situated immediately before each laboratory period, and the in-lab activities were aligned to reinforce the lecture material introduced that day. For instance, if students received a lecture about instrumentation and reading diagrams, the in-laboratory tasks would relate to identifying specific flow meters and diagram elements in multiple pieces of equipment in the laboratory. Weekly assignments were associated with these activities. After this rotation period, students would settle on a final piece of equipment to conduct a standard laboratory experiment. Lecture content would specifically align to planning, data analysis, and presentation. The final presentation was used as a mechanism to deliver instructor feedback and improve the overall final report. Initially, the lecture component was given in-person, but subsequent offerings pivoted the lecture to online video modules that were to be completed before attending the laboratory session each week. The modified course also had more specific instruction about instrumentation, equipment, and reading flow diagrams. Additional details about the traditional and revised course can be found in prior published work assessing student laboratory skills [4].

These data presented here represent a cohort of students for the first offering of the updated laboratory course, which used in-person lectures and not video lesson modules. Of the students who participated in a pre-laboratory and post-laboratory survey, 47 of these students completed the traditional Lab I course, while 18 students completed the modified Lab I course.

Methodology

Our intent with this work was to examine these data through a phenomenological lens. With this method, we seek to capture the "lived experience" of a group of people [7]. In our study, this group of people is comprised of upper-level chemical engineering students, and the event these students experience is the first chemical engineering laboratory course. Thus, we employed multi-dimensional survey tools to capture the students' first experiences in the laboratory.

The details of the complete study can be found in previously published work [removed for review], but students completed a self-assessment of laboratory skills (i.e., "How well do you feel like you can do a specific skill associated with lab?") and a direct laboratory skills test (i.e., "Can you answer questions related to a given P&ID (piping & instrumentation diagrams)?"). The same surveys were administered to students at the start of the first laboratory course and immediately after that same course, with the only modifications being made to verb tense in some prompts.

Both assessments included open-ended responses. For instance, the self-assessment included some prompts that allowed students to explain what skills they expect to gain in the laboratory course (or had gained, in the case of the post-test). The laboratory skills test sometimes asked students to justify a selected multiple-choice answer with a short paragraph. Open-ended responses to one of these prompts were analyzed for this study.

Prior to beginning analysis, several decisions were made. First, we needed to frame our research questions in a way that would ensure we had an appropriate inquiry that aligned with the type of data available. In other words, we needed to define the scope and nature of the question that would allow us to see the full experience in the data. Ideally, the research questions, the data collection, and data analysis methods should be crafted in tandem. Admittedly, by the time we began our qualitative analysis, we realized that we had not taken the time to intentionally design this portion of the study. We were trying to retrofit research questions and hypotheses onto the data we already had collected, rather than letting those questions inform the data collection process. Additionally, by the time we started this qualitative analysis, we had already analyzed the quantitative data, and our interpretation of those results informed some of our hypotheses. Once we examined the type of responses, we had available we realized the research questions needed slight revision to create better alignment. To avoid this pitfall and self-imposed limitation in future studies, researchers may wish to review the quality management process model outlined by Walther *et al.* [8], in which distinct quality strategies are applied to evaluate the validity and reliability of both stages, that of data generation and data analysis.

Finally, with our already collected data and our refined research questions, we decided the best-suited method for our purposes was to use the thematic analysis procedure outlined by Braun and Clark [5]. Broadly, thematic analysis involves the identification and analysis of patterns present within data sets. These patterns, or themes, capture some recurring response or meaning within the data set. These themes can be generated in two ways: inductive ("bottom up") or theoretical/deductive ("top down"). Inductive analysis lets the data drive the way themes are identified; the themes arise naturally through examination of the data without a pre-existing theoretical framework. Deductive analysis analyzes the data through a lens of a theoretical framework, which may help answer specific research questions. Then examining themes, a researcher must also decide if these themes are to be at the semantic or latent levels. Semantic-level are identified within the explicit, surface-level meaning of what is provided, while latent-level themes examine the underlying attitudes and ideologies that formed the response. Ultimately, we took an inductive approach to theming, with some themes focusing on semantic features (what specifically the student was talking about) while others focused on latent features (why was the student mentioning a certain element in a certain context).

Having established the above guidelines, the thematic coding procedure described by Braun and Clark was used [5]. This method consisted of six steps, summarized below, along with our process. Some alternative practices we discovered through conducting this analysis are noted, including brief justification for deviating from the published guidance.

1) **Familiarizing yourself with the data:** Anonymous student responses to the open-ended questions were loaded into Dedoose, a qualitative analysis software that allows collaborators to access data and code. In accordance with IRB, the key for student identifiers was held by a third party not actively involved in the assessment. Dedoose made it easy to read through each open-ended response to become aware of the types of responses that were being written. Lacking software like Dedoose, Microsoft Excel or Google Sheets can also allow for collaboration when coding. All authors read all responses, documenting notes about trends, observations, and interesting aspects. A log was created to document researcher observations, questions, and actions.

2) **Generating the Initial Codes:** After familiarizing ourselves with the data, we assembled a list of initial codes. In generating codes, we considered statements we found striking, surprising, intriguing, and/or disturbing about the responses [9]. In some instances, the tone and wording of the responses helped to sort responses. For example, students who wrote very brief responses that showed little reflection (i.e., "idk", "Nothing") were coded as "impertinent", while a longer, more nuanced response about a student's own perceived growth in the class was labeled as "authentic". We also paid attention to skill-based responses (i.e., "I can do…") vs. attitude-based responses (i.e., "I feel like…"). Some students had notably consistent or inconsistent responses over time and were labeled "consistent" or "inconsistent." To focus the codes, we kept the research questions present, and noted it was difficult to approach data without thinking of existing frameworks for themes. Ultimately, a preliminary list of codes was established.

   Equipped with these preliminary codes, we split the entire data set into thirds and independently started applying codes systematically without distinction between class cohort. While codes for content (i.e., responses that specifically addressed a communication skill, appreciation for safety, understanding of instrumentation or equipment, etc.) were straightforward, reading the responses made it clear that a student's interpretation of the question and the coder's reading of that student response could also play a role in choosing which codes to apply. Three sets of responses were selected for all researchers to code to assure an initial degree of inter-rater reliability.

   After the first round of applying preliminary codes, evaluators raised questions and discussed issues that arose. The subsequent discussion yielded two key take-aways: (1) we arrived at a revised code list more aligned with the data and the research questions, and (2) an established a more consistent and effective coding strategy. For more guidance on a variety of specific coding strategies, we refer readers to *The Coding Manual for Qualitative Researchers* [10] but we briefly discuss the phenomena of "lumping" vs "splitting" codes here. The "lumper" strategy involves applying a code to a large section of text, while leaving the option open for more detailed subcoding later. The "splitter" strategy splits responses into smaller codable instances. A lumper may apply one code to a whole response, while a splitter may apply seven different ones, for instance. Both approaches have pros and cons. Lumping is quicker and helps categorize phenomena easily, but it can miss fine details. Splitting can highlight extra details but is much more time consuming and may miss contextual aspects located elsewhere in the response. Some evaluators originally found themselves splitting excerpts, with one code per excerpt, but after discussion it was agreed that that some of these split codes, in fact, better served our intentions as lumped codes (several codes per excerpt).

The team took these strategies and independently applied them to the rest of the data. To ensure that the research team was applying codes consistently, we met after each completing a different third of response coding. This strategy allowed us to compare observations and use consistent wording throughout. Then, each researcher would move to the next third of the responses that had already been coded by another to apply their own coding. Once all the data had been independently coded by all three researchers, the codes were compared and condensed, with discussions to resolve discrepancies taking place.

3) **Searching for Themes:** Once the codes had been generated and applied, the results were reviewed and organized into major themes. To complete this step, each investigator arranged the codes into thematic maps based on the essence of the student responses to start to examine the relationship between the codes. (One preliminary map is shown in Figure 1 as an example). We then compared maps to find commonalities and discuss differences, with the intent to use these as a framework for discussing differences in responses over time, and between the two cohorts. At this stage, groupings of laboratory objectives from other sources [6, 11] were also considered to inform the discussion.

   Some of our chosen codes clearly related to the physical experience of being present in a laboratory setting (i.e., working with specific equipment or software). Others related to the act of being knowledgeable about conducting and analyzing an experiment (i.e., planning, troubleshooting, analysis, and justification). Another common theme was related to the communication of results in various forms. There was also an undercurrent in several responses relating to the students' self-actualization, a feeling like they had gained relevant skills or attained critical experience. At this stage, the exact pairing of codes to themes was broad, so further refining was required.

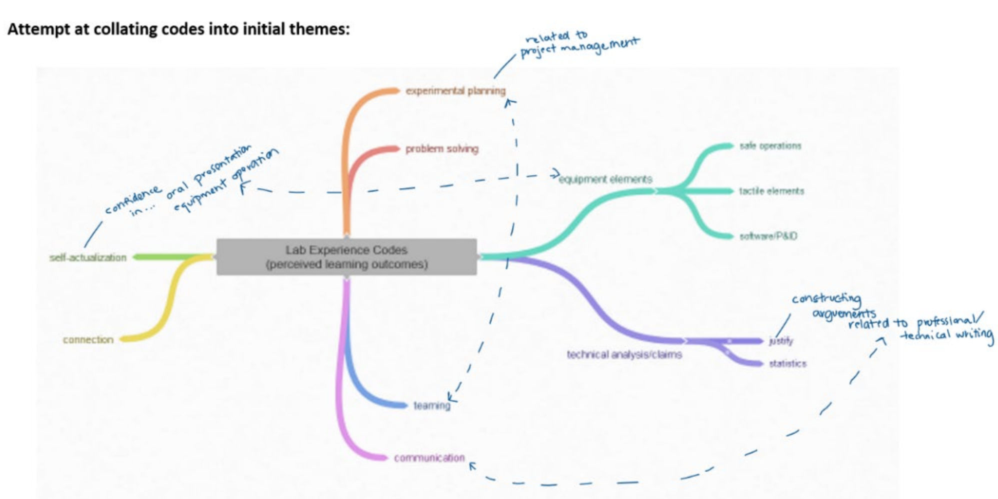

Figure 1. Example attempt at collating codes into initial themes.

4) **Reviewing Themes:** After initial thematic maps are established, this next phase described by Braun and Clarke involves two levels of review [5]. The themes are first reviewed for alignment with the coded excerpts, and the second level considers the themes relative to the full data set. Due to the simplicity of some responses, we were not able to ensure every theme was supported by each corresponding coded excerpt, however exemplary excerpts were noted. Modifications to these themes were made (for example, a fourth theme was added) until it was deemed by the investigators that the themes were in good agreement and accurately reflected the data set.

   A noted deviation we took in this work was to make use of code frequency charts to inform and affirm the existence of final themes. While grouping codes into broader themes without quantifying the data serves the analysis of longer excerpts containing complex ideas pertaining to one's experiences, the nature of the research questions and quality of the responses in this study lend themselves toward an approach referred to as content analysis (see Note 5 in Braun and Clarke [5]), which focuses on frequencies of words or phrases. Reviewing code frequencies allowed us to observe shifts in the prevalence of codes over time and between cohorts, which provided the basis for the final themes. The final thematic map differed significantly from the original grouping of codes, in part because our research questions aimed to capture the nature of any shifts observed over time and any notable difference among cohorts.

5) **Defining and Naming Themes:** Once the themes were solidified, the themes could then be defined in a way that captured their essential quality. The goal of this step is to end up with nomenclature that clearly defines each theme. Importantly, it should also be clear what each theme is not by the end of this phase as well. This step was accomplished by identifying exemplary responses and producing a short-form report for our internal department review. Defining these themes occurred organically as we set out to describe to our colleagues the reoccurring patterns observed the data.
6) **Producing the Report:** Preparing the report is the final opportunity for analysis, including specific selection of examples or data presentation that address the research question. Discussion of how each theme relates to and addresses the research questions is critical. This paper is that report. The short-form report has been adapted into the results and discussion presented in this paper.

Results

We report qualitative data using two approaches: a description of the responses based on thematic analysis, and a 'quantization' of the coded qualitative responses. Both approaches stem from coding the student responses, which were gathered from both cohorts (traditional and revised courses) before and after the laboratory course from a pre- and post-lab survey.

<u>Description of student responses:</u>
Student responses to these questions both before and after the course ranged in length and complexity, with some using only a few words, such as "data and error analysis", or "understand scientific articles", and others as long as four complete sentences:

> "I expect to have a better understanding of writing papers and reports suitable for a more industrial setting as opposed to my current strength in writing that is most suitable for an academic setting. My statistical analysis skills also need some work, as well as my

understanding of instrument calibration, as many of the instruments I am most familiar with are suited for small scale experimentation rather than large scale. My teamwork skills also need a certain amount of work, as I tend to work alone most of the time, especially when it comes to CHE classes. Most of my team working skills come from low skilled retail jobs and CHEM classes."

While nearly all responses mentioned topics that align with recognized relevant learning objectives, of the 130 total responses (combined cohort N = 65, two responses each), two were noted as either impertinent or too sparse to fully assess (e.g., "idk", "Nothing. I feel like I've gained remarkably little from this.") and came from responses after the course.

After reading all responses, codes were developed, defined, and in some cases organized (in some cases sub-codes belonging to a code were used for further distinction) and excerpts within responses were tagged as containing one or more codes (see Table 1). Each excerpt typically corresponded to one student response. The number of codes applied to each excerpt ranged from 0 to 10, with an average number of 3 codes per excerpt.

Across all student responses (among both cohorts) the most frequently occurring code was communication, followed by technical analysis/claims, and self-actualization.

Table 1: Description of codes

Code	**Description**
communication	writing, delivering, formatting an oral and/or written report
connection	connection of topics from other courses with the laboratory, connection of laboratory course to the CHE discipline, one's future career, or professional competencies
equipment elements	having to do with exposure to laboratory equipment (specific or general), including:
safe operations	operation safety, ability to conduct safe shut down
software/P&ID	interpreting documentation, using specific software tools
tactile elements	calibration, troubleshooting, following SOP, general hands-on use of equipment
experimental planning	researching background information, conducting an experiment aligned with interests/objectives, planning around new pieces of equipment
problem solving	working through an unexpected technical issue, mentions or implies problem solving
self-actualization	expressing personal confidence in a particular skill, as an engineer, or generally
teaming	working in a team or relating to project management
technical analysis/claims	broadly refers to analyzing data
justify	mentions supporting or validating technical claims with data or reputable sources
statistics	mentions analysis by applying statistics

The essence of student responses and the extent to which they shifted over time were considered using frameworks from literature [2]. Several students expressed anticipation of aspects of lab that lie in the psychomotor domain ("familiarizing myself with all of the different equipment in the lab workroom" [code: equipment elements]) and then after the course articulated a response aligned with the cognitive/affective domain ("giving an oral presentation without feeling nervous" [code: self-actualization, communication]). In another such example, this student first expects to be able to "apply chemical engineering principles to actual processes" [code: connection, equipment elements] and at the end, their response includes a capacity for communication as well as an attitude, specifically their self-confidence,

> "This course developed the professional side of my skills quite a bit with reference to writing a report and presenting the information. Before this course I would have been very uncomfortable attempting to do something like that." [code: connection, communication, self-actualization]

Other students exhibited the reverse shift: first an anticipation of learning related to the cognitive/affective domain ("develop[ing] communication skills[,] design experiments[,] deal[ing] with unexpected situations in the lab[,] writ[ing] technical report[s]" [code: communication, experimental planning, problem solving]) and then highlighted their ability to manipulate equipment ("I can use the equipment which we used in this lab (TFF system)" [code: tactile elements]). Further still, some students mention the same topic(s) consistently both before and after and for others, their before and after responses both pertain to several domains. Additionally, some students' first response mentioned multiple objectives while their post response focused on one aspect, as if they arrive with many expectations but after the course one stands out prominently.

<u>Describing the data with code frequency charts:</u>
To better understand the frequency in which these codes appeared together, we look at code-co-occurrence charts. Each chart shows the number of times one response (either a "pre" or "post" response) from any student in the cohort was tagged with both the code from the column and the code from the row. For example, in Figure 1A, a response was tagged as both connection and communication 11 times. Color scales are relative to each figure, not across figures. This is helpful, as each cohort contains different number of students (Revised cohort N = 18; Traditional cohort, N = 47), but can also be misleading if you only look at the colors, as the darkest shade corresponds to different values within each subfigure.

In looking from Figure 1A to Figure 1B, code co-occurrences within responses from students who took the traditional course are initially somewhat scattered with few expectations coded for safe operations and software/P&ID. By the end of the course they concentrate around the overlap of self-actualization and communication, using statements such as,

> "After lab, I feel much for [sic] comfortable presenting on a technical topic. I previously had little comfort with this because I had trouble explaining things in a way that people with limited background knowledge might understand."
>
> "I am definitely much more comfortable presenting technical concepts to a general engineering audience!"

A

	communication	connection	equipment elements	safe operations	software/P&ID	tactile elements	experimental planning	problem solving	self-actualization	teaming	technical analysis/claims	justify	statistics
communication	NA	11	6	1	0	4	11	9	9	4	12	0	5
connection		NA	4	1	0	3	5	6	7	3	8	1	3
equipment elements			NA	1	0	3	3	2	3	4	3	0	1
safe operations				NA	0	0	0	0	0	0	0	0	0
software/P&ID					NA	0	0	0	0	0	0	0	0
tactile elements						NA	3	2	3	1	1	0	2
experimental planning							NA	8	6	4	9	0	4
problem solving								NA	5	3	7	0	2
self-actualization									NA	3	7	0	4
teaming										NA	3	0	1
technical analysis/claims											NA	0	4
justify												NA	0
statistics													NA

B

	communication	connection	equipment elements	safe operations	software/P&ID	tactile elements	experimental planning	problem solving	self-actualization	teaming	technical analysis/claims	justify	statistics
communication	NA	9	1	1	1	0	4	6	17	2	10	3	1
connection		NA	0	0	0	0	2	3	7	0	3	2	0
equipment elements			NA	1	2	0	1	0	1	0	1	0	0
safe operations				NA	1	0	0	1	1	0	1	0	0
software/P&ID					NA	0	0	0	1	0	0	0	0
tactile elements						NA	0	0	0	0	0	0	0
experimental planning							NA	3	3	0	7	2	1
problem solving								NA	4	1	5	2	0
self-actualization									NA	4	6	0	0
teaming										NA	0	0	0
technical analysis/claims											NA	1	3
justify												NA	0
statistics													NA

Figure 1: 1A shows code co-occurrence for students' expectations ("pre") before the traditional laboratory course and 1B shows students' capabilities ("post") after the traditional course.

In looking at Figure 2A, co-occurrences within responses from students in the revised course initially appear in a similar scatter to those in the traditional course (Figure 1A), and then shift to other codes (see Figure 2B), with over 50% of the responses coded with technical analysis/claims and with notable frequency of equipment elements, safe operations, software/P&ID, and experimental planning. Here is an example where the student's first response mentions two broad objectives including communication, and after the revised course mentions specific technical abilities:

> Pre: "I expect to be able to give an effective oral presentation and be able to handle any questions afterward well. I also expect to be able to use lab equipment much better."
>
> Post: "I could not identify some uncertainties and calculate them properly before this course. I am now able to understand a PFD/PID."

A

	communication	connection	equipment elements	safe operations	software/P&ID	tactile elements	experimental planning	problem solving	self-actualization	teaming	technical analysis/claims	justify	statistics
communication	NA	3	6	1	1	4	1	2	6	1	6	0	1
connection		NA	4	2	1	2	1	3	2	1	3	0	0
equipment elements			NA	1	2	7	1	2	4	0	5	0	0
safe operations				NA	0	0	0	1	1	1	1	0	0
software/P&ID					NA	1	0	0	1	0	1	0	0
tactile elements						NA	1	2	3	0	4	0	0
experimental planning							NA	1	0	0	2	0	0
problem solving								NA	2	1	3	0	0
self-actualization									NA	1	4	0	1
teaming										NA	1	0	0
technical analysis/claims											NA	0	1
justify												NA	0
statistics													NA

B

	communication	connection	equipment elements	safe operations	software/P&ID	tactile elements	experimental planning	problem solving	self-actualization	teaming	technical analysis/claims	justify	statistics
communication	NA	2	2	3	2	0	4	1	2	1	4	0	1
connection		NA	1	2	1	0	1	1	1	0	2	0	0
equipment elements			NA	2	4	2	4	2	2	0	4	0	0
safe operations				NA	3	1	2	1	1	0	3	0	0
software/P&ID					NA	2	3	1	1	1	4	0	1
tactile elements						NA	1	1	0	0	2	0	0
experimental planning							NA	1	2	1	4	0	1
problem solving								NA	2	0	3	0	0
self-actualization									NA	2	3	0	1
teaming										NA	1	0	1
technical analysis/claims											NA	0	2
justify												NA	0
statistics													NA

Figure 2: 2A shows code co-occurrence for students' expectations ("pre") for the revised laboratory course and 2B shows students' capabilities ("post") after the revised course.

It is also worth noting several observable shifts in code frequency among the two cohorts observable in Figure 3 below. Responses coded for self-actualization (expressing confidence, often in reference to written and oral communication) increased in the traditional course (26% to 45%) and declined in the revised course (39% to 28%), while responses coded for safe operations, software/P&ID, or experimental planning all increased in the revised course (11% to 28%, 11% to 33%, 11% to 39%, respectively) and were observed less frequently by comparison at the end of the traditional course or even declined (2% to 4%, 0% to 6%, 34% to 21%, respectively). While efforts were in place to avoid self-selection of participants into these courses, we acknowledge that we cannot assume the interests and abilities across cohorts was initially uniform and that these shifts may be attributed to factors beyond simply the courses themselves. We are not attempting to conduct a robust statistical analysis, and thus we exercise caution when interpreting the significance of these results.

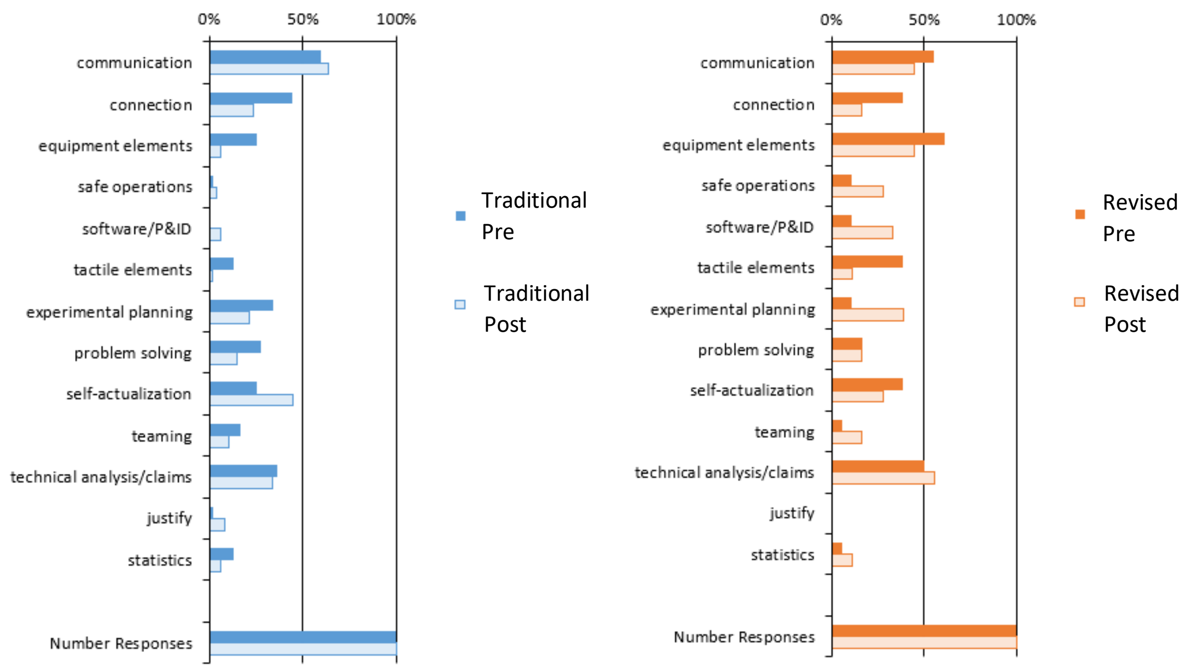

Figure 3: Code frequency for expectations ("pre") and for students' capabilities ("post") after the traditional laboratory (left, blue bars) and the revised laboratory course (right, orange bars).

Discussion

There are four key points, or themes, we'd like to highlight from the analysis of student responses:

Students entered lab anticipating the written and oral report. Across both the traditional (T) and revised (R) cohorts, while there is a range to their reported expectations, communication is most mentioned. Phrases like "give a full oral presentation", "know how to write technical reports" or "develop communication skills" that were coded for communication appeared in over half of student responses regarding expectations (T: 28/47, R: 10/18). Students clearly anticipate this aspect of their first laboratory course, which aligns with our perceptions of the course's historic reputation among students. At the end of the course, students across both cohorts had more distinct responses. In the traditional course, students frequently mentioned their confidence in communication. For the revised student responses, codes for experimental planning and equipment elements were as prominent as communication. This aligns with the changes in emphasis in the revised course. Activities (Data Analysis Memo, HRI rotations, emergency shut-down, etc.) that specifically underscored safety and equipment familiarity, alignment of experimentation with the project objective, and justification for technical claims using collected data appear to have shifted the focus of the course experience when it comes to students' reflection on what they can do by the end.

Students in the traditional course remained heavily focused on their written and oral reports. A key grade item in the traditional course is a group presentation followed by questions from their peers and professors, along with an individual report submission. We saw in the data that this aspect was most anticipated among all students, and many students in the traditional course experienced a fulfilment of those expectations. One student wrote:

> "After lab, I feel much for comfortable presenting on a technical topic. I previously had little comfort with this because I had trouble explaining things in a way that people with limited background knowledge might understand."

Even among students whose initial response didn't center on written or oral communication, many students in the traditional course chose to write about it at the end of the course. For example:

> Pre: "I expect to be able to design experiments, collect data in an organized fashion, interpret that data through statistical analysis, and submit professional documentation based on experiments I run. I also hope to be able to enhance my hands-on experience with various chemical engineering processes and to apply that experience to my future career options."
>
> Post: "I can now better organize laboratory data to make it presentable to our own laboratory group as well as to a more generalized audience. I can also make more effective visual presentations for a larger audience that better depicts our data and conclusions."

These outcomes are somewhat anticipated given the nature of the traditional laboratory course. Prior to the post-laboratory assessment, students had just completed a major laboratory report and a presentation on their laboratory project. Having recently received feedback on these aspects, students may have been more likely to mention communication skills in the assessment.

Students in the revised course were more likely to mention a broader array of laboratory course elements. While students in the revised course still had to produce a short written deliverable, there was a shift in emphasis among class activities and grade items away from the final written and oral report. Responses from students captured more diverging experiences. One way to frame this scattering is to consider the knowledge domains Feisel and Rosa use to group common laboratory objectives [6].

Responses from the revised course were frequently coded as technical analysis/claims. For example, one student mentioned knowing "how to work some of the machinery and instrumentation that is in the lab", and another stated "I can understand the limitations of what can be analyzed and tested with its instruments. Also, I have a better idea of how to design experiments for units." Safety was also mentioned with greater frequency among the revised cohort. One student mentioned "[I can] calibrate instruments needed for measurements, use computer software effectively, determine safe working conditions in a laboratory." These responses overlap with objectives that cut across all domains: cognitive, affective, psychomotor. That students reflect and acknowledge a wider set of experiences, including ones that engage the psychomotor domain, may be particularly important as we think about the intentional scaffolding of these objectives within the first laboratory course and subsequent courses in the sequence.

It is important to mention the connection between interest and learning and that we recognize there may be a strong relation between student interest and academic achievement. Additionally, data from small cohorts are more likely to be influenced by a few students with unique interests and motivations. Notably, we saw that before the courses began, the largest difference between cohorts in coded expectation responses was found in the percentage of responses coded with equipment elements (T: 26%, R: 61%). Some students in the revised course may have been pre-disposed to engaging the psychomotor domain, and thus, we cannot necessarily claim the revised course structure is the singular factor that impacted the students experience.

Students in both classes experienced "connection" and "self-actualization". Two codes that did not squarely fit into the traditional laboratory objectives were connection and self-actualization. Yet, students across both cohorts wrote about these experiences. Some expected to gain some form of "understand[ing] how experimental data and error relate to theoretical concepts discussed in coursework" and others mention "understand[ing] connections between theory and practice." Most responses with self-actualization related to communication, such as "hav[ing] more experience writing formal scientific lab reports" but others mentioned other skills, such as "feel[ing] much more confident in conducting error analysis, and understanding why those calculations are important" or being able to "trust my own decisions and thought processes in the face of adversity from group members."

These codes were observed in both cohorts both before and after the course. While lab can feel exhausting to students, they are leaving the first class with a sense of interrelatedness and accomplishment. A student's feeling of accomplishment may not always align with demonstrated mastery of an ability, yet researchers have shown the importance both performance and competence (defined as a student's self-perception of ability to perform engineering tasks and understand engineering concepts) have in one's sense of belonging and preparedness for success in engineering [12]. Additionally, the idea of *professional role confidence*, proposed and measured by Cech et al., is positively associated with the likelihood engineering students go on to pursue engineering careers [13].

Conclusions and Future Considerations

Students enter lab with a variety of expectations and interests, which may shift over the time of the course. These encompass a range of objectives which we can categorize across a range of learning domains. The differences observed in student responses generally track with the specific activities emphasized in the traditional and revised courses. As we continue to consider scaffolding these learning objectives throughout our lab sequence, we hope these results will help us make informed and intentional decisions regarding the specific domains of learning. We also hope this serves as a resource for other educators considering qualitative research to enhance assessment of engineering education, particularly around curricular changes.

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