Exploring student beliefs of traditional physics laboratory coursework in relation to authentic research

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Undergraduate research has been shown to have many benefits for students, including degree persistence, feelings of belonging, and transferable research skills. However, there are barriers that prevent students' access to research experiences. Course-Based Undergraduate Research Experiences (CUREs) are a potential avenue to lower such barriers. Within STEM fields, physics has been identified as lacking CUREs, prompting our initiative to develop a physics framework to provide instructors with effective practices to develop their own CUREs. Understanding of students' perceptions of the connection between coursework and components of authentic research will inform the framework and assess impacts of course transformations. We probed student beliefs through writing assignments in a traditional lab course, exploring how authentic research elements were viewed in the context of the course. We present the results from analysis of these assignments and discuss how these findings will be used to inform the framework and new physics CUREs.

2024 PERC Proceedings edited by Ryan, Pawl, and Zwolak; Peer-reviewed, doi.org/10.1119/perc.2024.pr.Kretchmer

I. INTRODUCTION & BACKGROUND

Undergraduate research experiences have many benefits for a student's education [1–4]. These opportunities allow students to develop transferable research skills [5], and provide motivation to continue to pursue STEM degrees [4, 6]. Participating in undergraduate research also helps students build relationships with peers and senior scientists [7] and increases their interest in, and preparation for, the STEM workforce [8]. However, there are barriers that students may encounter when seeking traditional undergraduate research experiences (i.e., apprentice-style training with direct mentorship from a faculty member, postdoc, or graduate student). These barriers can range from a lack of research opportunities [7] to financial or other personal barriers experienced by students [9, 10], resulting in interested students being excluded from undergraduate research.

A potential avenue to increase access to undergraduate research is through course-based undergraduate research experiences (CUREs). A CURE involves students in authentic and relevant research through a course, allowing an entire class of students to participate in research, rather than only individual students [11]. Literature indicates that CUREs must involve five key pillars:

1. Use of scientific practices
2. Immersion in discovery
3. Broader relevance
4. Promotion of collaboration
5. Implementation of iteration

Full definitions of each pillar can be found in Refs. [7, 12].

CUREs have been implemented in degree programs across STEM disciplines, particularly in biology and chemistry [13]. Research on CUREs has shown similar positive impacts as traditional undergraduate research experiences, such as increased retention and persistence in STEM degrees and desire to pursue STEM fields professionally [14, 15]. Students have also reported gains in confidence, an understanding of how scientists think, and increased technical and analytical skills [16, 17]. However, physics CUREs have been lacking in the CURE literature [13]. There have been a few examples of physics CUREs [18–20]. A recent example is the Colorado PHysics Laboratory Academic Research Effort (C-PhLARE) CURE implemented for three semesters at the University of Colorado Boulder (CUB). In response to the COVID-19 pandemic, the C-PhLARE CURE was designed as a remote course for a large (∼400-600 students per semester) introductory physics laboratory course. Students in the course examined potential mechanisms behind coronal heating of our sun. A full description of the course can be found in Ref. [21]. After participating in the C-PhLARE CURE, students reported moderate gains in confidence in their ability to do science, understanding what everyday research looks like, and feeling comfortable discussing science with others. They also agreed that their research was relevant to the scientific community and provided a sense of personal achievement [20–22].

Based on the positive impact of CUREs in other STEM disciplines, combined with the result from the C-PhLARE CURE, physics students would benefit from the creation of additional CUREs. To this end, we are working to (1) identify the challenges and opportunities to the implementation and sustainability of physics CUREs and (2) build a new framework of effective practices to support the development of CUREs in physics. The framework will include tools such as assessment methods to measure the impact of the course on students and training materials for graduate teaching assistants (TAs) and undergraduate learning assistants (LAs), as well as guides for many other parts of creating a CURE. The framework will be tested and iterated on through the development of a CURE in a sophomore-level physics lab course at the CUB, which will begin in Fall 2024. The course is required for physics, engineering physics, and astrophysics majors and serves ∼200-250 students per academic year. Throughout the course, we will gather input from all stakeholders, including instructors, TAs and LAs, and undergraduate students participating in the course.

The goal of this work is to present results from analysis of the data collected from the traditional version of the course. One set of data is from an end-of-semester writing assignment. The analysis of these data aims to address the question of 'How do students connect course experiences to components of authentic research?'. Similar data will be collected from students who participate in the CURE. These data will then be compared to evaluate the effectiveness of the CURE on students ideas around the key CURE pillars. Here, we will outline the data collection and analysis of the written student responses in the current traditional lab, discuss initial results from this analysis, and present the next steps in the development of the framework.

II. METHODOLOGY

In the current version of the physics lab course at CUB, students are given the opportunity to work through their choice of 5 of 10 different 'modern physics' experiments (e.g., photoelectric effect, Hall effect). The student lab guides are very prescriptive for both how the experiment should be performed and how the analysis should be done. The students begin the course with two weeks of onboarding activities (e.g., computational tutorials, safety trainings, course assessment pretests). After this, students complete the experiments in two-week blocks. The first is spent working through the experiment and collecting data, while the second is dedicated to data analysis and writing a lab report. This process then repeats for the four other experiments chosen by the student. The students take data in pairs, but complete their own analysis and reports. At the end of the semester, the students completed a writing assignment via Qualtrics [23]. Student responses were graded for engagement (one to two paragraph response for each question), rather than "correctness." The assignment consisted of nine questions, which are based on CURE pillars [7]. The questions are listed in Fig 1. We collected writing assignments from 183 students from Spring and Fall 2023 semesters for analysis in this work. All identifying data were removed from the student responses by the in-

1. Describe the experiences you had in PHYS 2150 that you believe were similar to real experimental physics research.
2. What did you experience in PHYS 2150 that you believe is **NOT** similar to real experimental physics research.

Did you experience the following in PHYS 2150:

3. **Scientific practices:** Using the practices, methods, tools, or processes of science (e.g., asking questions, gathering and analyzing data, developing and critiquing interpretations and arguments, communicating findings).
4. **Iteration:** Repeating experiments/analysis or parts of experiments/analysis in order to refine your understanding or the experiment.
5. **Failure:** Experiencing failure or setbacks that allow you to learn from your mistakes and make improvements.
6. **Relevant discovery:** Making meaningful discoveries that are relevant to the larger scientific community, advance our understanding of the world, or have a positive impact on society.
7. **Autonomy:** Having autonomy, ownership, or decision-making power to pursue your own scientific interests, choose experimental designs, or interpret results.
8. **Collaboration:** Working with peers, instructors, mentors, or the larger scientific community to share expertise and knowledge or leverage resources to achieve more significant results than you would have been able to accomplish individually.
9. **Successful science:** Producing data or results, experiencing success in experiments, or answering research questions that achieve scientific goals/objectives set by you or your research team.

FIG. 1. Questions from writing assignment. For all nine questions, students were asked to respond in one to two paragraphs. For Questions 3-9, students were asked to explain whether or not they experienced this component in the course, if they did experience it, what was the experience, and if they did not experience this component to describe why not.

structor prior to analysis, so we do not have any demographic information.

For the analysis, we used a standard qualitative coding process to analyze the responses [24]. We started with a set of *a priori* main codes (Tab. I) based on the specific topics covered by the questions in the assignment. During subsequent passes through the data, we supplemented the *a priori* codes with additional emergent subcodes (indicated by *italics*). These subcodes captured the details of how students said they engaged with a concept, as well as when they explicitly said they did not engage with it. Using the Failure main code as an example (Tab. I), through emergent coding the specific types failure the students encountered (e.g., *inaccurate results, misinterpretation of procedures, time constraints, troubleshooting code*) and how they responded to that failure (e.g., *acceptance of failure, accepting feedback, frustration, trying again*) became subcodes. There are anywhere from 2-24 sub codes for different main codes. The codebook was applied to the entire assignment. An abbreviated version of the codebook showing only the main codes can be seen in Table I. After finalizing the codebook, we conducted an inter-rater reliability (IRR) process. Authors MK and RLM applied subcodes to a set of 20 excerpts that were previously coded with two main codes - *Ideas about real research* and *Real research in course*. After each researcher separately coded the excerpts, they came together and discussed the subcodes. We calculated Cohen's kappa for both before and after discussing the codes. For *Ideas about real research* the pre-discussion $\kappa = 0.75$ and post-discussion was 0.92. For the *Real research in course* code, our pre/post values were 0.74/0.89. Cohen's kappa values above 0.8 are considered to be in 'nearly perfect agreement' [25], meaning our IRR results are acceptable. At this point, MK coded all remaining student responses.

III. RESULTS & DISCUSSION

For the work presented here, we focus on the results around student beliefs about discovery, agency, and failure/success.

Beginning with discovery, students were asked if they believed they experienced making meaningful discoveries that were relevant to 'the larger scientific community, advancing our understanding of the world, or having a positive impact on society'. Unsurprisingly, many students said they did not experience discovery in the current course (78%). A common belief was that all the experiments in the laboratory course had already been done before, with one student saying:

> I completed...experiments that have been completed before. The experiments I did only verified constants or relationships that are already known and verified. It would be different if I completed different experiments that verified constants in a new way, but I only did experiments that scientists have already done.

However, some students did believe they made relevant discoveries in the sense that they encountered something that was new to them. One student said:

> I experienced finding meaningful discoveries [that] deepened my understanding of the world, which on a fundamental level are the building blocks to scientific and societal advancements.

While we did not expect students to experience new discovery though the use of highly guided labs with known outcomes, it is useful to identify what discovery means to students (e.g., *real-world application* (8%), *contributing new knowledge* (64%)). We also found that some students believed they did engage with discovery when they encountered *ideas that were new to them* (10%) or when an experiment *helped them better understand a concept*. When designing the new course and CURE framework, it will be important to consider all types of discovery.

TABLE I. Abbreviated Codebook for the writing assignments. These are only the highest level codes; no subcodes are shown.

Main code	Definition
Ideas about real research	Student ideas about what comprises authentic experimental research
Real research in course	Students beliefs on how they did or did not encounter real research in course
Agency	Student views on how they did or did not have agency in the course
Collaboration	Student views on how they did or did experience meaningful collaboration in the course
Iteration	Student views on how they did or did not experience iteration in the course
Failure	Student views on how they did or did not experience failure in the course
Successful science	Student views on how they did or did not experience successful science in the course
Discovery	Student views on how they did or did not experience discovery in the course
Relevance	Student views on if their coursework was relevant outside of the classroom
Scientific practices	Student views on how they did or did not use authentic scientific practices in the course
Career Clarification	Experiences in the course that helped students clarify career goals

Next, when responding to whether or not students believed they experienced agency, the most common source of agency listed was their ability to choose which five experiments to conduct throughout the course (63%):

> Getting to choose which five experiments to do over the whole semester clearly gave me autonomy in the course. In addition, what order I could do these in and who I could work with made the whole course autonomous.

While acknowledging their agency in choice of experiment, some students felt that having a limited set of experiments and having no input on the design of the experiments or the experimental procedures hindered their agency:

> So although I had some choice, I did not have any choice in experimental design or have ownership over the experiments.

Feelings of a lack of agency regarding the experimental design was further expressed by students finding the experiments to be extremely prescriptive. The lab guides gave students too many directions leaving no room for individualized thinking and decision making.

> For the actual experiments I mostly just followed the prescribed set of instructions. I never felt like I was really choosing anything. Even the lab report followed a prescribed format.

However, there were also students who believed they had agency by physically conducting the experiment themselves and because they were allowed to analyze (e.g., select the coding language for analysis) and interpret their results from each experiment and decide how to present their findings in their reports, with one student saying:

> Autonomy was present in the interpretation of results though, as there was no necessary oversight during this portion. It was satisfying to get to critically think about the results and draw conclusions, even if this pertained primarily just to sources of uncertainty.

While it took relatively little for students to feel that they had some agency (selecting which labs to complete and in which order), students indicated the opportunity to participate in experimental design and make decisions regarding analysis was important. To allow for agency in the new CURE, student choice will be important throughout the process, even with a predetermined research question. As indicated above, these decisions can be 'small,' but still have impact, so the framework will encourage folks to consider including choices at all scales ranging from decisions regarding their particular analysis to how they present their final results to the instructor.

Finally, we looked at students views of failure and success. While not common, there were students who believed that they *never experienced failure in the course* (7%). These students felt that as long as they followed directions and asked questions, they could not fail, as described by one student:

> I didn't experience failure in these labs. The instructions were very clear and the TAs were very helpful. These factors helped reduce the likelihood of failure.

However, most students said that they did experience failure (93%). Students identified failure as *taking bad data* (28%), *having inaccurate results* (31%), *any trouble faced with coding and equipment* (36%), *getting bad grades on their lab reports* (25%), and *misinterpretation of procedures* (30%), with one student saying:

> Constantly, with every experiment, every lab section, and every writeup I found myself making every possible mistake...I may have had more of these experiences because I did not read the lab manual before coming to class, so it took a couple of tries to get data flowing as it should. During the data analysis often I would find myself only beginning to understand the theory behind the lab as I worked with it, and I would realize I was misinterpreting portions of data.

Students also expressed that experiencing failure resulted in frustration and an increase of the amount of time spent on their lab with one student saying:

> There were a few labs where my results did not match the expected value. Some of these were do to unit conversion errors while some of them were due to errors in the data collection. Either way, these problems resulted in frustration. Every so often, a lab that should've taken about an hour to analyze took up to 3.

While many students acknowledged that they were frustrated with failures they faced, they responded to failure in a variety of ways (e.g., *accepting feedback* (32%), *trying again* (89%)); students also responded by *accepting the failure* (37%) and moving on, despite wanting to have 'better' results:

> This was extremely frustrating...I always wanted to produce a lab report that had accurate and well analyzed results, but over the semester, I learned that the error in my data collection wasn't something I could change after a certain point, so I had to accept defeat and write about why my answer did not agree with the accepted value. This was extremely hard to do, but at the end of the day...there was a point where I had to move on.

Frustration and failure are parts of the scientific process - nothing works perfectly the first time [26]. It will be important to build support into the CURE for students to be able to productively deal with frustrations and failure [27]. Some of this support will come from the graduate TAs and instructor modeling what to do when things do not go as planned and working together with the students through these points. Materials on how to best prepare the TAs to guide students through through feelings uncertainty and frustration will be included in the final framework.

When considering student ideas of success, we found a majority of students believed they had success if they *produced the expected result* (90%). It was uncommon for anything else to be mentioned. Below is an example of a student who felt that getting the correct results boosted their confidence.

> Multiple experiments produced the desired result for me. This was always exciting to see that the data you spent nearly two hours collecting actually meant something. This boosted my confidence as a scientist and also made the lab reports easier to write because I didn't have to write about my failures or...why my results didn't look as desired. This was a cool feeling and I hope to experience it again in the future when I'm working on novel experiments in a research lab.

Of the students who thought they did not experience successful science, many felt this way because *their results did not agree with the known value* (59%). Finally, connecting back to the idea of discovery, some students felt their success was reduced because the *lack of relevance* (41%), caused by no new discoveries being made and the experiments being done at a lower level of precision than what had been done in the past, which can be seen in the following quote:

> However, some of the success felt minimized by the fact that we were repeating experiments that had originally been done so long ago and yet still more accurately than we were often able to.

Because when doing authentic research there is not a known 'correct answer' to aim for, it may be challenging for students to view their results a success by traditional measures. Therefore, it will be important to focus on aspects that students who have participated in other CUREs have identified as successes (e.g., successful teamwork[22], success overcoming obstacles[28]). The framework will outline how to engage students in conversations about what success means for the research process as compared to a traditional lab experiment.

IV. SUMMARY & FUTURE WORK

The analysis of these writing assignments have provided helpful feedback into how students connect their experiences in a traditional, sophomore-level experimental physics lab to components of authentic research. Although some students may experience discovery by doing an experiment that was "new to them," the majority of students do not believe that they encountered discovery in their traditional lab course. Both aspects of discovery (novel research and confidence with concepts new to them) will be featured in the framework. Additionally, a majority of students believe they have experienced failure in their course and responded in a variety of ways, ranging from trying again to accepting failure without correcting it. It will be important for instructors and TAs to model acceptance and perseverance through frustration and failure, as well as provide support and encouragement for students during this process. Finally, a majority of students believe any success they have in their traditional lab course is based solely on whether or not they found the expected results. Shifting student focus to other types of success (e.g., teamwork and problem solving) will be a priority in the new course and in the framework.

For our next steps, we will consider the themes from the other coded responses not discussed here. We will then interview students who have taken the traditional course to get more in depth knowledge of some of these themes. The results of the writing assignment and interview analysis (both from the traditional course and CURE course) will be translated into components of the framework.

ACKNOWLEDGMENTS

This work is supported by the NSF Mathematical and Physical Sciences Ascending Postdoctoral Research Fellowship program (PHY 2316504), PHY 2317149, and STROBE NSF Science and Technology Center DMR-1548924.

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