Student perspectives on “Successful Science” in a physics CURE and traditional lab course

Rachael L. Merritt, Micah Kretchmer, and H. J. Lewandowski
Department of Physics, University of Colorado Boulder, Boulder, CO 80309, USA and
JILA, National Institute of Standards and Technology and the University of Colorado, Boulder, CO 80309, USA

Laboratory courses are essential in undergraduate physics education. The American Association of Physics Teachers recommends labs focus on developing students’ experimental and professional skills, scientific reasoning, confidence, as well as other goals. Course-based undergraduate research experiences (CUREs) offer a promising approach to achieve these goals–providing authentic research opportunities to entire student cohorts while lowering barriers to research participation. However, few physics CUREs are documented in the literature. Broadly, our work aims to determine effective practices for developing and implementing physics CUREs. When developing a CURE, instructors should consider how to align course learning goals, such as engaging students in authentic research, with both the structural elements of a CURE and students’ perceptions of those goals. Here, we examine how students engage with one aspect of authentic research, the idea of successful science, through an end-of-semester reflection assignment. We present the results of our analysis and compare how students in a CURE and those in a traditional lab course define successful science.

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I. INTRODUCTION & BACKGROUND

Laboratory courses are an important component of undergraduate physics curricula, providing students with opportunities to engage in hands-on experimentation. According to the American Association of Physics Teachers (AAPT) Recommendations for the Undergraduate Physics Laboratory Curriculum key learning goals for these courses include developing students' experimental skills, such as modeling, designing experiments, analyzing and visualizing data, and effectively communicating physics, as well as fostering scientific reasoning, confidence, and professional skills like teamwork and collaboration [1].

To achieve many of these goals and help students develop a stronger appreciation for the development of scientific knowledge, it has been shown that students should engage in lab activities with unknown outcomes [2, 3], likely because open-ended activities allow for more authentic engagement with the processes of experimental physics [4, 5]. Despite these benefits, many laboratory courses continue to rely on prescriptive lab activities with step-by-step procedures that aim to confirm known results or reinforce lecture content [6, 7]. As a result, many recommended learning outcomes are not being fully realized [8, 9].

Course-based undergraduate research experiences (CUREs) offer a promising alternative for achieving the recommended laboratory learning goals, and have been recommended in the the Effective Practices for Physics Programs (EP3) guide [10]. As defined by the CURE Network [11], the five key components, or pillars, of a CURE are (1) the use of scientific practices, (2) discovery, (3) broadly relevant or important work, (4) collaboration, and (5) iteration [12]. Students participating in CUREs have demonstrated increases in self-efficacy, motivation, persistence, content knowledge, and analytical skills [12, 13]. These outcomes have been shown to be similar to outcomes identified from participation in traditional undergraduate research experiences (UREs) [14]. Unlike traditional UREs, which are typically available to only a small number of students, CUREs offer entire classes the opportunity to explore research questions relevant to the scientific community, while reducing barriers to participation [12, 15–17].

Despite the benefits of CUREs and recommendations to implement them, physics has been identified as a STEM discipline with relatively few examples of CUREs documented in the literature [18]. To broaden the reach and impact of physics CUREs, instructors need guidance not only on designing and implementing these courses, but also on assessing whether they meet their intended learning goals. Effective implementation depends on aligning instructional practices and learning objectives with authentic research elements.

In addition to ensuring that the five CURE pillars are present, it is critical to understand students' perceptions of what defines authentic research. Goodwin et al., 2021 [19] developed a framework that includes the CURE pillars alongside additional student-identified elements such as failure, autonomy, and notions of successful science. When developing a CURE, instructors should consider both the structural components that define a CURE and the ways students engage with or identify aspects of authentic research.

In this work, we analyze an end-of-semester reflection assignment in which students articulate their experiences of successful science within a physics CURE. Using data from the first semester of a perovskite photovoltaics physics CURE at the University of Colorado Boulder (CU Boulder), we aim to answer the following research questions:

1. In a physics CURE, what do students identify as successful science?
2. How do students' views of what constitutes success compare between a traditional lab course and a CURE?

II. COURSE OVERVIEW

PHYS 2150: *Experimental Physics 2* is a one-credit, sophomore-level laboratory course required for physics, astrophysics, and engineering physics majors at CU Boulder. Prior to its transformation, the course followed a traditional lab format focused on classic modern physics experiments, such as the Franck-Hertz experiment and the Millikan oil drop experiment. Throughout this paper, we refer to this version of the course as the 'traditional lab.' In its current form as a CURE, students investigate how environmental stressors–such as temperature and illumination–affect the external quantum efficiency and current density vs. voltage of metal halide perovskite photovoltaics. This is an active area of energy and materials research, given the high efficiency, tunable bandgap, and low production cost of perovskite photovoltaics [20–22]. However, improving the long-term stability of these devices under environmental conditions remains a significant challenge [23].

The CURE consists of three components: project onboarding, data collection and analysis, and investigating student-formulated research questions. Each component takes approximately one-third of the semester. Students are assigned to teams of 3 – 4 students and work with in these teams for the entire semester. The project onboarding prepares students for subsequent activities by introducing teamwork, reading scientific literature, and hands-on training with data collection and analysis.

After the collection of baseline data during the onboarding period, the perovskite devices are placed into stressing stations, which consist of a hotplate and a specific wavelength of illumination via high power LEDs, and the course transitions to the data collection and analysis phase. Each week, the devices are removed from the stressing stations and students take external quantum efficiency and current density vs. voltage measurements for each of the six pixels in their sample. During each week of data collection, students receive a Google Colaboratory (Colab) notebook to guide their data analysis. Colab is an online platform for running Jupyter Notebooks. New Python tools are introduced weekly throughout this phase, such as plotting from multiple files, visualizing error bars, and performing linear regressions and other fitting techniques. Around the midpoint of the semester, student teams propose a research question, which will be referred to as 'team-formulated question' for the remainder of this paper, and an analysis plan based on the collected aggregate data from all teams. The teams iterate on this proposal in response to instructor feedback.

In the final phase of the course, students complete the analysis to answer their team-formulated question and communicate their findings. Results are shared in two formats. First, each team creates a one-slide summary of their findings, all of which are compiled and sent to the science PI ahead of the final class meeting. This allows the PI to highlight student work and discuss how their data will contribute to ongoing research during that last meeting. Second, each team writes a research memo that outlines their question, data selection and analysis methods, key findings and interpretations, and suggestions for future work.

III. METHODOLOGY

The data for this work come from an end-of-semester reflection assignment given via Qualtrics [24]. Students responded to nine open-response questions motivated by the Goodwin et al. authentic research framework [19]. They were adopted from a reflection assignment used in the Colorado Physics Laboratory Academic Research Effort, a remote, large-enrollment, solar physics CURE developed and implemented at CU Boulder [25, 26]. At the beginning of the assignment, students were given the following prompt: *For each of the following text boxes, please explain whether or not you experienced this component in PHYS 2150. If you did experience this component, describe that experience OR if you did not experience this component of real experimental research, describe why not.* They were also given definitions of the nine topics being probed. Responses were graded for engagement, not "correctness." Students in the traditional lab and the CURE were provided with the same version of the reflection assignment. In future work, we will analyze additional course artifacts to determine if student perceptions of authentic research are consistent across different types of assignments and reflections and if additional elements emerge.

We used a standard qualitative coding process for analysis [27], beginning with a set of *a priori* codes aligned with the authentic research components probed in the assignment. In subsequent passes through the data, we added emergent subcodes under the main codes as needed. Authors MK and RM conducted an inter-rater reliability (IRR) process on the codebook using data from the traditional lab [28]. Cohen's kappa indicated acceptable agreement [29]. Because few additional emergent codes arose during the analysis of the CURE responses, we did not repeat the IRR process for the CURE codebook. Students could provide multiple relevant ideas in response to a single question and a single student statement might be assigned multiple subcodes. As a result, the percentages for subcodes within a main code may not equal 100%. We collected and analyzed three semesters of data (Sp23-Sp24; N=253) from the traditional lab and have currently analyzed the responses from the Fall 2024 semester of the CURE (N=103). The preliminary results from the traditional lab (Sp23-F23; N=183), additional details about the reflection assignment, and the IRR process are available in Kretchmer et al., 2024 [28].

For the work presented here, we will focus on what students identified as experiencing successful science. In the reflection assignment, students were given the following definition of successful science, adopted from Oliver et al., 2023 [26]: *Producing data or results, experiencing success in experiments, or answering research questions that achieve scientific goals/objectives set by you or your research team*. Students were not provided with any additional definitions, as we wanted to see how they interpreted and defined these concepts within the context of their own experiences. Table I displays the **Successful science** and **Lacking successful science** subcodes used in our analysis.

IV. RESULTS & DISCUSSION

A. Successful Science in a physics CURE

We identified three main themes in students' reflections on how they experienced successful science in the CURE. First, 56% of students reported experiencing successful science when they were able to answer their team-formulated research question. As one student explained:

> *I also feel like we were able to achieve the scientific goals set by our research team, as we were able to answer our research question and find an equation for the relation between rate of decay and stressing temperature, which was our research objective for our group.*

Second, 37% of students felt they experienced successful science when they were able to collect data.

> *I think my group had a good amount of scientific success as we were able to get data on most of our pixels each week and sometimes getting data on all the pixels.*

The *Collecting Data* subcode was often double-coded with either the *Answering Research Question* subcode or the third theme subcode: *Producing Results*.

We found that 40% of students reported experiencing successful science when they produced results. Within this third theme, three sub-themes emerged. The first sub-theme is students interpreting the value of their results in terms of what their team accomplished:

> *We also got meaningful results for our research question. We concluded that our research question was true as the cells closest to wall in storage degraded a bit faster than the rest. We were able to hit most of our goals and objectives by getting a large amount of data and answering our research question accurately.*

In the second sub-theme, students viewed the success of their results in a broader scientific context, emphasizing the contribution of their findings to colleagues outside of their team and to the field of perovskite photovoltaics:

TABLE I. Successful science and Lacking successful science subcode definitions. The total percentage, with 95% confidence intervals, of student responses coded with each subcode are shown in the third and fourth columns for the CURE (N=103) and the traditional course (N=253). Codes that were added to the codebook after analyzing CURE data are indicated with an asterisk (*).

		Percentage of Responses (%)	
Subcode	**Definition**	**CURE**	**Traditional**
	Experienced successful science through:		
Answering research question*	Answering their team-formulated research question	56 ± 10	0
Producing Results	Producing results or interpretations from their data	40 ± 10	11 ± 4
Collecting Data*	Collecting data	37 ± 9	0
Enjoyable time in the lab	Enjoying time in the course/lab	4 ± 4	2 ± 2
Valuable time in the lab	Being in the lab and learning new things	11 ± 6	9 ± 4
Finding expected results	Finding the expected answer to the experiment	0	80 ± 5
Boosting confidence	Improving confidence to do science	0	1 ± 1
Helping others	Helping others throughout the course	0	1 ± 1
	Experienced a lack of successful science through:		
Not Meaningful Results	Being unsure or viewing their results as insignificant	6 ± 3	0
Limited Data Collection	Believing their data was bad or incomplete	6 ± 3	0
Lack of Relevance	Seeing no connection to modern science/greater scientific community	0	2 ± 2
Failing to get expected results	Not finding the expected answer to the experiment	0	13 ± 4

> *I think our group was able to provide helpful results to the scientific community. With our research question and analysis of data, I think our research helped provide information to the research of PVCs.*

The third sub-theme that emerged is students describing feeling they experienced successful science even when their results were null or inconclusive. For some, this reflected a developing understanding of the realities of ‘real’ research. As one student wrote:

> *I was a little disappointed when the answer to our research question was that the independent variable had no effect on the dependent. However, I learned that a lot of times this is a valid and still important result. Just because something is constant doesn’t mean it isn’t helpful...I thought that was a very true to life finding.*

Others described experiencing successful science by focusing on their consistent contributions to the larger research effort, such as producing data visualizations and supporting the shared dataset, even when their own results were inconclusive:

> *While our results were inconclusive, I still felt like our research and analysis was valuable...[S]eeing our graphs produced every week felt like a success. Us collecting data every week also helped other people answer their research questions.*

We also found instances of students questioning the definition of successful science provided in the reflection assignment. These critiques often stemmed from students’ views about how science works. One student challenged the idea that successful science is defined by a single final result, instead emphasizing the value of the entire process:

> *I question the definition of “success" here. We collected data and were able to use the machines properly, but our final data did not have clear trends in it, indicating that further experimentation is necessary...This is a normal result to be expected in science...We were successful in obtaining and analyzing data, even if we did not conclusively answer our research question.*

This echoes the previous point of students viewing null or inconclusive results as successful, while also pushing back on externally imposed definitions of success. Another student went further, explicitly rejecting the idea that science should be classified as successful or unsuccessful:

> *Successful science is any science. This course is taking measurements and making thorough conclusions based on evidence. That alone is science[...]Science should not be concerned with categories of successes and failures, but pathways that all lead forward. If you come across a dead end, you still learn something to pass onto others...That’s successful science, or I would rather call it effective science, which I feel this course demonstrated to the fullest.*

While many CURE students reported experiencing successful science, some also reflected on aspects of their work they viewed as feeling unsuccessful. Students described a lack of successful science when they were unsure if their results were meaningful or believed their results were insignificant (6%). Some also attributed their sense of unsuccessful science to collecting poor-quality or insufficient data (6%).

B. Successful Science in a Traditional Lab

In the traditional lab, two themes were reported by more than 10% of the students. By far, the most commonly identified theme for experiencing successful science in the traditional lab was *Finding Expected Results*. Approximately 80% of students identified finding expected result for an experiment as their primary indicator of successful science. One student said:

> *I had experiences of successful science in this course. I felt very proud of my work when we achieved the expected result experimentally with a good error range.*

A smaller portion ($\sim$11%) of students identified producing results as a success, with one student saying:

> *Seeing our data come together with graphs during data analysis was also a part of this as it helped us see that we had successfully observed a scientific relationship.*

Producing results was often double-coded with *Finding expected results*, highlighting the prominence of students viewing a 'correct' or expected answer as successful science. We also see this theme in what students identified as experiencing unsuccessful science, with the most frequently reported subcode being *Failing to get expected results* (13%).

C. Comparing Student Definitions of Successful Science in a Traditional Lab versus a CURE

When comparing student views of successful science in the CURE and the traditional lab, students in both modalities associated successful science with *Producing Results* from their data. However, they differed in who they believed their results were valuable to. In the CURE, students described their results as valuable to their team, classmates, and the science PI or broader scientific community. In contrast, students in the traditional lab did not describe their results as inherently valuable, but instead framed the production of results in terms of completing tasks set by the instructor, with one student noting:

> *I was correct in all of my experimental labs except for one in which I got an uncertainty value larger than the actual measured value. But, I was mostly successful in answering the questions set by the instructor.*

Beyond this limited overlap, there were significant differences in what students in each course viewed as successful science.

Although students in both courses were provided with the same definition of successful science, we observed notable differences in how they described their experiences. In the traditional lab, the most commonly identified marker of success was *Finding Expected Results*. Students in this course tended to equate success with obtaining a "correct" answer. In contrast, students in the CURE highlighted success elements aligned with Goodwin et al.'s authentic research framework [19]: answering their team-formulated research question, collecting data, and producing results. These students felt they experienced successful science even when their results were null or inconclusive. This difference is not surprising, given the fundamental distinctions between traditional lab courses and CUREs. However, these findings are significant in confirming that the pervoskite photovoltaics CURE effectively engages students in activities that support their perception of participating in authentic research.

There is also a difference in what students identified as unsuccessful science. In the traditional lab, the most commonly identified unsuccessful science experience was not getting the expected results. In the CURE, students believed they were unsuccessful if they felt their results were not meaningful or that they had not collected enough data. Notably, CURE students did not equate successful science with finding a 'correct' answer. This may offer a response to instructor concerns that students who have only participated in traditional labs may have difficulties acclimating to the discomfort with the unknowns and 'messiness' of experimental science [30].

V. SUMMARY & FUTURE WORK

These student reflections provide valuable insights into how students perceive successful science in both a CURE and a traditional lab context. We found that while students in the traditional course equated scientific success with obtaining an expected or "correct" result, students in the CURE viewed success more broadly as the process of collecting data, generating results, and addressing their team-formulated research question. Unlike in the traditional lab, CURE students recognized that null or inconclusive findings could still represent meaningful and successful scientific outcomes. Additionally, CURE students described experiencing unsuccessful science when they were uncertain if their results were meaningful or felt they had not collected sufficient data. In contrast, students in the traditional lab viewed lack of success primarily as failing to obtain the "correct" answer.

As next steps, we will continue to iterate on the pervoskite photovoltaics CURE. Our analysis of additional student artifacts will offer insight into how students perceive and define success in a CURE. These findings can inform instructors' choices around feedback and how they frame course goals, helping to ensure that the course design reflects the five required components of a CURE. Collectively, this work will contribute to a set of effective practices for designing and implementing physics CUREs, with the goal of supporting the creation of additional CUREs in the field.

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