Science practices in calculus-based introductory physics laboratory courses

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Our research focuses on student engagement with science practices across introductory chemistry, biology, and physics laboratory courses as defined in the *Framework for K-12 Science Education* and the Next Generation Science Standards (NGSS). In this study, we use the Three-Dimensional Learning Assessment Protocol (3D-LAP) to look for evidence of potential to elicit science practices in introductory calculus-based physics laboratory materials. We found the science practices of Developing and Using Models, Analyzing and Interpreting Data, Using Mathematics and Computational Thinking, Constructing Explanations, and Engaging in Argument from Evidence to be consistently embedded into the physics laboratory curriculum. Meanwhile, there were few opportunities for students to engage in practices such as Asking Questions, Planning Investigations, Evaluating Information, Communicating Information, and Designing Problems and Solutions. We discuss the implications of these findings for the development of future physics lab curricula and instructor pedagogy, and by extension, student learning.

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I. INTRODUCTION

Improving science teaching and learning is a continuing goal of science education. Efforts toward this goal include examining opportunities for students to actively engage with the subject matter in laboratory spaces. Lab classes are particularly well-suited for helping students develop the experience they need to enter the workforce as scientists. However, a national survey found that there is a mismatch between introductory physics students' and instructors' goals for laboratory work, especially related to whether the goal of laboratory activities is to reinforce conceptual understanding, develop laboratory skills, or both [1, 5]. Despite much discussion among physics educators about which laboratory skills are central to physics labs [2-7], little work has been done to assess students' development and engagement with laboratory skills [8,9]. Given that universities invest precious resources into funding laboratory teaching spaces, there have been calls for evidence that laboratory courses provide students with holistic and authentic experiences [10-13].

Current research into physics laboratory activities emphasizes the need to incorporate more scaffolded and open-ended activities and the impact of these changes on students' conceptual and epistemological understandings [14,15]. While these efforts have been shown to positively impact students' beliefs about the nature of science, science affect, and confidence in performing physics lab tasks [1], the impact on student engagement with laboratory skills is unclear. This nebulousness may stem in part from a lack of consensus regarding how lab skills are defined and is a significant challenge in examining the effectiveness of laboratory efforts.

Our work focuses on how science practices (SPs) are situated in laboratory curricula across introductory biology, chemistry, and physics. SPs are behaviors and activities that scientists frequently engage in and embody what students should be able to do with their science knowledge. Moreover, SPs are well-defined in the *Framework for K-12 Science Education* [16] and Next Generation Science Standards (NGSS) [17], allowing for more systematic assessment of what students do in the lab.

We use the Three-Dimensional Learning Assessment Protocol (3D-LAP) to characterize laboratory artifacts for their potential to elicit evidence of student engagement in SPs [18,19]. This protocol has been used in the past for characterizing college-level assessments across chemistry, biology and physics, as well as with laboratory activities in chemistry [20-22]. Research focused on science practices and the use of the 3D-LAP in physics laboratories is limited. Studies on SPs in physics have focused on either one or a few practices at a time [23,24], non-lab physics assessments (e.g., exams and assignments) [25,26], and lectures [27]. In this study, we analyzed lab artifacts from a calculus-based introductory physics course series for their potential to elicit evidence of student engagement with all ten SPs described in the *Framework* [16], with a goal to assess how they are situated in introductory physics laboratory curricula.

II. THEORETICAL FRAMEWORK

The *Framework for K-12 Science Education* [16] and the NGSS [17] provide systematic definitions of the SPs. While the *Framework* and NGSS were developed for use in K-12 settings, these documents, and the SPs specifically, have applications for all levels of education [20,21,28]. These documents describe SPs as behaviors that scientists engage in regularly as they *do* science. SPs help students engage in critical thinking, emphasizing a combination of knowledge and skills for explaining/reasoning about phenomena [7,28]. The SPs therefore demand simultaneous minds-on/hands-on engagement. The practices are shown below (see Table 1). For clarity and conciseness, specific SPs may be referred to by their corresponding practice number.

Table 1: The science practices described in the NGSS

P1: Asking Questions	**P6**: Constructing Explanations
P2: Developing and Using Models	**P7**: Engaging in Argument from Evidence
P3: Planning Investigations	**P8**: Evaluating Information
P4: Analyzing and Interpreting Data	**P9**: Communicating Information
P5: Using Mathematics and Computational Thinking	**P10**: Defining Problems and Designing Solutions

In this study, we used the 3D-LAP (science practices criteria for constructed responses) to examine laboratory artifacts for potential to engage students in SPs. This protocol describes criteria that lab activities are required to meet to be considered aligned with an SP(s). The criteria for Using Mathematics and Computational Thinking from the 3D-LAP are shown in Table 2.

Table 2: 3D-LAP criteria for Math and Computational Thinking

Using Mathematics and Computational Thinking
Students are asked to use mathematical reasoning or a calculation and interpret the results within the context of the given event, observation, or phenomenon.
1) Question gives an event, observation, or phenomenon
2) Question asks student to perform a calculation or statistical test, generate a mathematical representation, or demonstrate a relationship between parameters
3) Question asks student to give a consequence or an interpretation (not a restatement) in words, diagrams, symbols, or graphs of their results in the context of the given event, observation, or phenomenon

III. CONTEXT AND METHODS

A. Context

Our analysis is drawn from a calculus-based introductory physics series of courses at a primarily undergraduate-serving, medium-sized public university. The series consists of Physics 1, 2 and 3 over three quarters of instruction, and is required for most STEM majors. Physics 1 focuses on *Kinematics and Mechanics*; Physics 2 focuses on *Electricity and Magnetism*; and Physics 3 focuses on *Optics and Waves*.

Each course in the introductory physics series has both lecture and lab components. Our work focuses on the lab component only. As an initial step, we obtained the most recent laboratory teaching materials (laboratory manuals, pre-lab worksheets, and post-lab assignments) for the three courses in the introductory physics series. The lab curricula that we analyzed were designed with a strong emphasis on metacognition and a scaffolded instructional approach. We will discuss later how this approach may increase or limit how students engage with science practices.

B. Methods

All physics laboratory materials were manually coded for the potential to engage students in science practices using the criteria described by Laverty and colleagues [18] and Carmel and colleagues [19]. Each experiment in the manual is designed and written as a series of related activities. Each activity has a set of scaffolding questions that guide students toward a predetermined learning objective. Meanwhile, pre-lab and post-lab assignments are often composed of 1-2 questions. The pre-lab questions aim to prime students' ideas about concepts central to the lab activity. The post-lab questions are designed to revisit and extend pre-lab concepts, applying ideas recently developed in the lab to new situations.

We considered each lab, along with its pre- and post-lab assignments, as a unit of coding. Each lab is often comprised of several activities with multiple parts (for example: Activity 1, parts a, b, and c). Assigning a code to an activity signifies that there is sufficient evidence of that activity's potential to elicit a student to engage in the practice. For an activity to have sufficient evidence, it must meet all the criteria for a practice, such as the criteria shown in Table 2. Activities or questions that had the potential to elicit more than one practice were coded for multiple practices. The same practices can show up in a lab manual or assignment multiple times in different activities and questions.

All laboratory materials were analyzed by at least two independent coders. Before beginning full-scale coding and prior to discussion of differences, inter-rater reliability was calculated and showed that agreement in coding between individuals was 87%. Coding of the introductory physics series was completed over the course of about 24 months by coders working in pairs or trios. For each laboratory session, individual coders read and analyzed materials using the 3D-LAP to assign preliminary codes prior to meeting. Finally, the whole team met to share and discuss codes, resolving any discrepancies to reach full consensus (100% agreement) on final code assignments.

IV. FINDINGS

A. Presence and frequency of science practices

1. General patterns

FIG. 1. shows the presence and frequency of science practices in laboratory sessions across introductory physics courses. We define the presence of a SP as when a lab has the potential to elicit that practice at least once. We define frequency as the number of times a SP is coded in one lab session. We represent differences in frequency by varying the intensity of the blue color in FIG. 3.

PHYS 1										
Lab 1	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 2	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 3	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 4	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 5	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 6	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 7	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
PHYS 2										
Lab 1	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 2	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 3	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 4	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 5	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 6	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 7	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
PHYS 3										
Lab 1	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 2	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 3	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 4	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 5	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 6	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Lab 7	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10

FIG. 1. A heat map representing the presence and absence of science practices. Color is coded based on frequency, with deeper shades indicating additional instances of a SP (range is white = 0 instances to darkest blue = 5+ instances).

A total of 21 laboratory sessions across the three introductory physics courses were examined for evidence of potential to engage students in scientific practices. All 21 labs showed potential to elicit engagement in at least one SP, with most labs showing potential to elicit engagement in multiple (three or more) SPs. Additionally, many labs presented many potential opportunities for students to engage in the same SP (as reflected in the darker shadings in FIG. 3).

Across all the introductory physics laboratory courses, we found a strong emphasis on Developing and Using Models (P2; present in 100% of sessions), Engaging in Argument from Evidence (P7; present in ~90% of sessions), Constructing Explanations (P6; present in ~90% of sessions), Analyzing and Interpreting Data (P4; present in ~80% of sessions) and Math and Computational Thinking (P5; present in ~70% of sessions). The SPs that had lower potential for being elicited were Planning Investigations (P3; present in >10% of sessions) and Evaluating Information (P8; present in >10% of sessions). We found that no sessions provided evidence for the potential to elicit three of the defined SPs: Asking Questions (P1), Communicating Information (P9), and Defining Problems and Designing Solutions (P10).

2. *Comparison across the sequence*

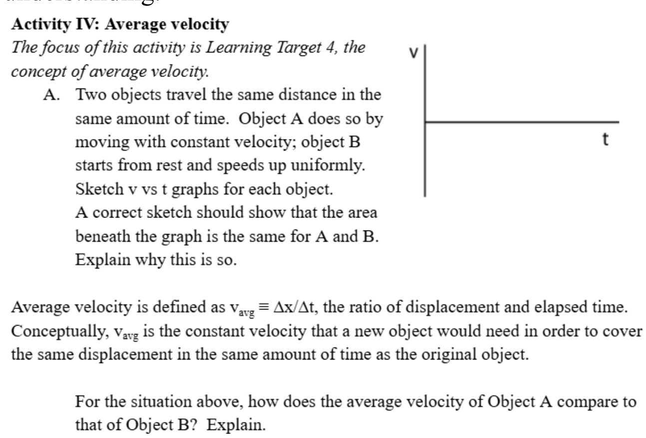
Across the introductory physics courses, the first sequence (Physics 1) puts more emphasis on SPs (showing potential to elicit engagement in 5 SPs on average in each lab session), compared with Physics 2 (with an average of 4 SPs), and Physics 3 (with an average of just under 4 SPs). We also noticed that P2, P6, and P7 are consistently emphasized across all three sequences. However, P4 and P5 are more strongly emphasized in the first sequence, with fewer instances over the next two sequences. Some other interesting observations as we look across the series are: *(i)* The lab session with the fewest potential opportunities to engage in SPs is at the end of the third sequence (Physics 3, Lab 7), coded to have potential to elicit only one practice, P2); *(ii)* P8 is only present twice in the first sequence during Labs 1 and 2, and once in the second sequence in Lab 7, and is completely absent from the third sequence; *(iii)* P3 is only present once in the first sequence in Lab 3 and once in the second sequence in Lab 7; and *(iv)* Physics 2, Lab 7 is the only lab where P3 and P8 (SPs that are relatively rare) are both present.

B. Science practices that are concurrently coded

Some science practices are often seen together in the same question and/or activity. Combinations of two or more of the following practices occur the most frequently: Analyzing and Interpreting Data, Using Math and Computational Thinking, Developing and Using Models, Constructing Explanations, and Engaging in Argument from Evidence. This list of SPs often has one or two potentially overlapping criteria, such as requiring an element of reasoning or interpretation.

It is relatively common for a lab activity in introductory physics to simultaneously elicit multiple SPs. For example, Activity IV in Physics 1, Lab 1 was coded as having the potential to elicit both P2 and P5 (see FIG. 2). This question combines the use of visual representation (the velocity vs. time graph) with mathematical relationships (the average velocity equation) so that, in tandem, the question meets the criteria for both Developing and Using Models (P2) and Using Mathematical and Computational Thinking (P5).

Students are asked to construct a representation that can be used to show the differences of v vs. t for each object, supported by further reasoning behind why they constructed their graph in a particular way (all criteria for P2 are met). Within the same context, students are also asked to consider a mathematical relationship between the two objects, using the provided equation, as well as provide an interpretation of what that means (all criteria for P5 are met). The construction of this pair of questions allows the two SPs to interlock and support the connections within the content, which then supports the student's learning and depth of understanding.


Activity IV: Average velocity
The focus of this activity is Learning Target 4, the concept of average velocity.

A. Two objects travel the same distance in the same amount of time. Object A does so by moving with constant velocity; object B starts from rest and speeds up uniformly. Sketch v vs t graphs for each object. A correct sketch should show that the area beneath the graph is the same for A and B. Explain why this is so.

Average velocity is defined as $v_{avg} \equiv \Delta x/\Delta t$, the ratio of displacement and elapsed time. Conceptually, v_{avg} is the constant velocity that a new object would need in order to cover the same displacement in the same amount of time as the original object.

For the situation above, how does the average velocity of Object A compare to that of Object B? Explain.

FIG. 2. Excerpt depicting Physics 1, Lab 1 Activity IV, A.

V. DISCUSSION AND CONCLUSION

A. "Near miss" activities

As coding of lab artifacts was underway, we often found instances of activities that fulfilled most, but not all, of the criteria needed to elicit an SP. Oftentimes, these "near miss" activities did not meet the full criteria for an SP because they lacked a prompt that would fully elicit student reasoning. This prompt for reasoning could be absent or as brief as "explain." In many of these cases, small modifications in the wording of question prompts would convert an activity from a "near miss" to having the potential to elicit SPs. An example of this could include expanding a prompt to "explain your reasoning behind your claim using evidence."

Prompts for reasoning require more direction to increase the likelihood of students responding to them in the way that is intended.

FIG. 3 shows an example of a “near miss”, which asks students to *make a claim* (Criterion 2) based on the *scenario that has been presented* before them (Criterion 1) by selecting one of the given options. The question then *asks for reasoning* behind the student’s selection (Criterion 4). Our analysis is that this question met 3 of the 4 criteria for the SPs Constructing Explanations and Engaging in Argument from Evidence. In this case, while the student is prompted to provide reasoning, they are not asked for scientific principles or evidence to support their claim (Criterion 3). By expanding this prompt as shown below in the blue text, this question would now meet all criteria for these SPs. Examples such as this suggest that existing curricula can be modified to meet more complete SPs in the short term without requiring major curricular overhaul.

1. A child uses one hand to charge a balloon by rubbing it against her shirt. She then holds a rod in her other hand and finds that the balloon and rod, when brought close to one another, repel. Select one of the following and explain your reasoning using scientific principles to support your answer:

a. the rod must be a conductor *b. the rod must be an insulator* *c. it could be either*

FIG. 3. Excerpt depicting PHYS 2 Lab 1 Pre-lab Activity 1 with suggested revision in the blue text.

B. Role of metacognition within labs

This particular physics lab curriculum was written with attention to metacognitive learning, and students are prompted to evaluate their own work several times during each lab activity. A criterion for Evaluating Information asks students to evaluate information from outside sources. Since students were asked to evaluate their own work, this activity does not meet the criteria for this scientific practice. However, we note that explicitly revisiting one’s own understanding is an effective metacognitive activity [29, 30].

Most of the “near misses” we encountered lacked prompts for expressing reasoning. Lab courses with “near misses” but that are designed to incorporate metacognition may have an advantage for students, as students are explicitly prompted to evaluate their reasoning. We suggest that students will reap the greatest benefits when explicit prompting towards defined SPs is coupled with metacognitive prompts.

C. Distribution of and connecting SPs in labs

In this study, we noticed a pattern of uneven distribution of SPs across the introductory lab series, with an emphasis on student verifying theory (cookbook-style labs) rather than proposing questions or driving their own investigations (reflected in the SPs identified as present). Developing and Using Models was present in every lab across the series and often appeared multiple times in each lab session. This pattern has been identified in several other studies [21, 22], which also show evidence that some SPs are over-emphasized (Using Math and Computational Thinking, Analyzing and Interpreting Data, Developing and Using Models, and Constructing Explanations), while others are underrepresented or absent (Asking Questions, Planning Investigations, Defining Problems and Designing Solutions, and Communicating Information). These patterns align with our analysis where practices that are tightly linked with content verification show up frequently while others are rarely or never seen.

As students enter upper-division courses and research settings, they are expected to proficiently engage with SPs. However, without frequent and repeated exposure to SPs in introductory courses, students are underprepared for entry into these spaces. All students (whether STEM majors or not) need engagement in SPs to develop crucial competencies, including critical thinking and scientific literacy.

Inclusion of the practices of Asking Questions, Defining Problems and Designing Solutions, and Communicating Information can be challenging to implement in already tightly scheduled or overburdened laboratory curricula. Short-term efforts to increase student engagement in these practices could involve instructors and TAs developing prompts that target practice criteria not currently met in the curricula, and engaging students in discussions around these prompts. However, long-term solutions for including these practices require intentional curricular (re) design.

Institutions invest significant resources into science laboratory courses. It is therefore important that students receive a meaningful science education with ample exposure to SPs. Our findings help identify ways in which SPs can be more effectively included as part of existing curricula, which may reduce barriers to inclusion. While identifying instances of SPs in our labs is an important first step, in order to determine how effective our lab materials are, an analysis of how students interact with those materials is necessary. Future work includes analyses of lab video data to determine how students respond to current prompts in our laboratory curricula.

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