Helping Students to “Do Science”: Characterizing Scientific Practices in General Chemistry Laboratory Curricula


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Supporting Information

ABSTRACT: Over the past 20 years research on reform efforts aimed at the chemistry laboratory has focused on different aspects of students’ experiences including increasing content knowledge, improving student attitudes toward chemistry, incorporating inquiry activities, and providing students a hands-on experience related to the chemistry concepts learned in lecture. While many of these efforts have been designed to incorporate inquiry activities, because this term is somewhat nebulous, it can be difficult to identify which aspects of the laboratory support inquiry. The Scientific and Engineering Practices outlined in the Framework for K–12 Science Education provide a new way to identify and characterize laboratory activities more precisely. This work compares two laboratory curricula in terms of the extent to which the curricula as a whole provide opportunities for students to engage in scientific practices and characterizes in which sections of a laboratory activity (prelab/procedure, data manipulation/analysis, conclusions/report out) students most frequently engage specific scientific practices. Further, this study demonstrates how a modified version of a published protocol for evaluating incorporation of science practices into assessment items (3-Dimensional Learning Assessment Protocol) can be used to evaluate laboratory activities in a systematic way. Ways in which such an analysis can inform and support the revision of laboratory curricula are also discussed.

KEYWORDS: Chemical Education Research, First-Year Undergraduate/General, Laboratory Instruction, Collaborative/Cooperative Learning, Student-Centered Learning

FEATURE: Chemical Education Research

INTRODUCTION

Goals of Laboratory Learning

Most scientists and science educators believe that the teaching laboratory is an essential component of learning in the sciences. In the late 19th century, postsecondary institutions introduced laboratory instruction for the purpose of developing skilled technicians and researchers. Currently, however, the teaching laboratory is expected to meet numerous other objectives. Several groups have identified goals for laboratory instruction, and though these differ somewhat from each other, they can be organized into several general categories: learning key science concepts, motivating and generating interest in science, developing laboratory skills, gaining an understanding of the practices used by scientists, working as part of a team, and learning time management. While there has been much debate about the utility of laboratory instruction for student learning in chemistry, the general sentiment remains that the laboratory is where students ought to gain an appreciation for chemistry as an experimental science as opposed to something that is abstract and theoretical.

The articulated goals of laboratory instruction suggest that the laboratory has great potential to support student learning in science; however, in Hofstein and Lunetta’s influential review of learning in the science laboratory, they report that there is little evidence to support attainment of these desired outcomes. Decades later, Hofstein and Lunetta point out that although we have learned much about what promotes conceptual change in the laboratory, there are still many factors that inhibit learning in this environment. The two most prominent factors are the following: (1) most laboratory experiments employ “cookbook” procedures that students can follow and execute successfully without thinking about the larger purpose of the investigations, and (2) assessments of laboratory learning largely focus on content knowledge and ability to perform specific techniques while neglecting students’ understanding of the practices of scientists and the purposes of laboratory investigations. Even though Hofstein and Lunetta’s
Table 1. Levels of Inquiry*

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>Corresponding Scientific Practices</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Confirmation: Problem area, methods of solution, and “correct” interpretations are given or are immediately obvious from either statements or questions in the students’ laboratory activity or textbook. Includes activities in which students simply observe or experience some unfamiliar phenomena or learn to master a particular laboratory technique.</td>
<td>None</td>
</tr>
<tr>
<td>1/2</td>
<td>Structured Inquiry: Laboratory activity proposes problems and describes how investigation should be conducted and how data should be analyzed so the student can discover relationships. Students must decide how to report results and conclusions.</td>
<td>None</td>
</tr>
<tr>
<td>1</td>
<td>Guided Inquiry: Laboratory activity proposes problems and describes how investigation should be conducted so the student can discover relationships he/she does not already know from manuals and texts. Students must determine how to analyze data and how to report results and conclusions.</td>
<td>Analyzing and interpreting data (see below for criteria)</td>
</tr>
<tr>
<td>2</td>
<td>Open Inquiry: Problems are provided, but students must determine methods as well as solutions.</td>
<td>Planning and carrying out investigations; Analyzing and interpreting data</td>
</tr>
<tr>
<td>3</td>
<td>Authentic Inquiry: Problems, as well as solutions and methods, are left open. The student is confronted with the “raw” phenomenon.</td>
<td>Asking questions; Planning and carrying out investigations Analyzing and interpreting data.</td>
</tr>
</tbody>
</table>

“See ref 15.

While an explicit focus on scientific practices in laboratory learning is relatively new, research has consistently supported the use of inquiry-based laboratory activities over traditional “cookbook” activities.\(^\text{11,12}\) Several approaches have been developed to characterize the instructional style or “level of inquiry” in a particular laboratory program based on the components (problem/question, theory/background, procedures/design, results analysis, results communication, and conclusions) provided to students and which the students must construct for themselves.\(^\text{13,14}\)

What is provided to the student and what is left open-ended at different levels are described in Table 1. The levels progress from most structured (confirmation), where essentially all parts of the investigation are mapped out for students, to unstructured (authentic), where students are expected to generate their own scientific question to investigate and then determine how to carry out and report the results of that investigation. Bruck, Bretz, and Towns\(^\text{15}\) used this rubric to characterize laboratory texts across astronomy, biology, chemistry, and physics, finding that most of the laboratory activities were at the lower levels of inquiry: levels 0 (confirmation) and 1/2 (structured inquiry).\(^\text{15}\)

This characterization of the levels of inquiry can be useful given that the literature has shown that inquiry instruction can have a positive effect on student conceptual understanding\(^\text{11}\) and there is some indication that the level of inquiry may affect students’ content knowledge and process skills at the high school level.\(^\text{16,17}\) Yet, as illustrated in Table 1, this method of characterizing inquiry instruction places considerable emphasis on developing procedures, something few scientists do from scratch, and the more experimental aspects of the science process, while not explicitly considering other important aspects such as developing and using models, using mathematics and computational thinking, constructing explanations, arguing from evidence, and obtaining, evaluating, and communicating information. The characterization of scientific practices, however, affords a lens to more explicitly and globally consider what types of activities students are engaged in during the laboratory activity. Further, Domin\(^\text{14}\) stresses that simply including “inquiry” or open-endedness in a laboratory curriculum does not necessarily facilitate the development of “scientific inquiry” skills, which are most akin to the current scientific practices. More recently, the Argument-Driven Inquiry (ADI) curriculum,\(^\text{18}\) which emphasizes the centrality of argumentation in the social construction of scientific knowledge,\(^\text{19}\) has been promoted as a means of assessment in the general chemistry laboratory. In this curriculum,
students are given the opportunity to not only hone their chemical knowledge through conducting and refining experiments, but also to develop and refine arguments on the basis of their experimental findings. This curriculum has been shown to help students produce better arguments and increase their engagement with the content being studied.20 The ADI curriculum is a good example of how to incorporate the practices of doing science into the instructional laboratory but is focused on the student product (the final argument) and the increase in lab practical exam scores.19,20 Other chemistry laboratory reforms have focused on trying to accurately model the enterprise of science research. For example, Cooperative Chemistry23 is a project-based curriculum in which teams of students work together to solve a problem or answer particular scientific questions. Projects are rooted in a real-life scenario to help students connect their experiments in the laboratory to the world outside.

It is important to point out that all of the laboratory curricular reforms mentioned here have had different goals in their implementation. Some aimed to increase the autonomy of students working in the laboratory13–15 while others focused on students constructing a strong argument from their collected data.18,20 The goals of the reforms certainly influenced how the reforms were assessed. However, regardless of the goal of the reform, one of the desired outcomes, whether explicit or implicit, was to more effectively engage students in the practices of scientists. The extent to which various curricula are able to do this is still largely unknown.

Assessing Laboratory Outcomes

Assessment of laboratory outcomes has varied in the research literature. With Cooperative Chemistry23 the curriculum has been shown to have positive effects on students’ metacognitive and problem-solving skills as well as to provide important professional development for the graduate teaching assistants facilitating the curriculum.22–24 More recently, the Meaningful Learning In the Laboratory Inventory (MILI), asks students to self-report whether their cognitive and affective expectations for chemistry laboratory have been met by a particular laboratory experience.25 The assessment of the CASPIE project focused heavily on students’ understanding of the nature of science.26

The NRC consensus study on undergraduate research experiences25 and Williams and Reddish26 have reported on the state of research on CUREs, Course-Based Undergraduate Research Experiences, noting that the assessment has been heavily focused on students’ perceptions of their own gains in research skills or their intent to pursue careers in science as opposed to evidence of engagement with practices or learning outcomes. To fill this void, Harsh and colleagues27,28 developed performance-based measures that are aimed at measuring the scientific thinking skills of students as a result of research experiences. These open-ended, short essay response questions give students the opportunity to demonstrate their problem-solving and reasoning abilities in an authentic chemical context, such as critiquing experimental designs or providing alternative explanations for results.27 Further, Maltese, Harsh, and Jung29 designed and validated a self-report tool to give students a means to report their cognitive and affective gains as a result of undergraduate research experiences. These instruments are representative of much of the laboratory assessment to date which has largely focused on the affective domain. Though this is certainly important, we might also expect that assessment strategies that focus on the more tangible laboratory outcomes should also be reported.

If the goal of a particular laboratory curriculum is to help students learn to “do science”, it makes sense to assess whether students are doing science, that is, engaging in the scientific practices.9 Once a construct is identified, the task of assessing that construct becomes much more tangible. It is then possible to identify criteria for the features that must be present in a task to elicit information that demonstrates understanding of a particular construct such as constructing an argument from evidence. An example of this is the 3D-Learning Assessment Protocol (3D-LAP),30 developed by an interdisciplinary group at Michigan State University, which provides criteria for each of the scientific practices identified in the Framework and has been used to determine whether assessment tasks in chemistry, biology, and physics30 have the potential to elicit student understanding of the practices. In this report, we extend the use of the 3D-LAP criteria to the characterization of the scientific practices in which students participate during laboratory activities. For this particular study, we did not focus on identifying the core chemistry content addressed by each laboratory activity; instead we looked at how activities in different curricula address or incorporate scientific practices. That is, instead of assessing changes in student attitudes or content gains with self-reported data, the units of assessment are the curricula, which gives a much more process-oriented view of what students are asked to do/engage in while in their chemistry laboratory.

Research Questions

The primary focus of this study was a proof-of-concept to characterize the extent to which scientific (and engineering) practices (SPs) are incorporated into existing chemistry laboratory curricula with the following research questions guiding our study.

1. To what extent can we reliably characterize when scientific and engineering practices are present?
2. To what extent are scientific and engineering practices explicitly addressed in a traditional and a project-based laboratory curriculum?
3. When scientific and engineering practices are explicitly addressed in a laboratory investigation, in which parts of the investigation (procedure/prelab, data manipulation/analysis, discussion questions/report out) do they typically appear?

■ METHODS

This study investigated two different general chemistry laboratory curricula: one that used multilevel project-based laboratory activities and one that followed a traditional format using weekly laboratory activities. The courses that employ these curricula are typical general chemistry courses in that they primarily serve first-year students that are pursuing a major in a STEM field. The multilevel projects were adopted from, or modeled on, a published, project-based laboratory curriculum, Cooperative Chemistry,21 in which students design and enact their own procedures, analyze their own collected data, and make claims, arguments, and explanations based on their evidence. Each of the projects is situated in the context of a scenario or problem that the students are asked to solve. Prior to each week’s lab meeting, students are asked to prepare by answering guiding questions to help them devise a plan as a group to solve the given problem. This includes dividing up

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tasks because projects are designed to require more experimental work than any individual can accomplish in the time allowed. Once in lab, the students execute the plan that they have designed as well as troubleshoot and adjust their approach if necessary. At the end of each lab period, the groups take time to share and synthesize the data collected and then determine the next steps for accomplishing the remaining project goals. At the culmination of each project, students report their findings in one of the following ways: evidence-based argument, formal written laboratory reports, research posters, or oral research presentations.

The traditional curriculum composed of weekly laboratory investigations was similar to the chemistry laboratory curricula analyzed in the study by Bruck et al. Each activity contained overall objectives for the activity (e.g., synthesize acetylsalicylic acid), some background reading, a procedure for students to follow, and some follow-up questions designed to help guide students in the analysis of their data and application of concepts. The report-out mechanism was most often a set of worksheets from the students’ laboratory manual.

To identify the presence of scientific practices (SP) in laboratory activities, we used an expanded version of the Three-Dimensional Learning Assessment Protocol (3D-LAP). The 3D-LAP provides criteria for evaluation of both selected- and constructed-response assessment items in order to determine whether those items are capable of eliciting evidence that students are engaging in a particular practice. The Supporting Information accompanying the publication provides numerous examples of how these criteria should be applied so that others can effectively use this instrument. The constructed-response criteria for the scientific practices from the 3D-LAP were used in this work. This instrument was originally designed for written assessment tasks to be used primarily on examinations, rather than for laboratory activities, and therefore, some practices were not addressed in the original version of the 3D-LAP. For example, defining problems and designing solutions were practices that were omitted from the original 3D-LAP as the team could not find examples of them in the over 3500 assessment tasks that were originally coded, and in fact, the Framework defines them as “engineering practices”. However, defining problems or designing solutions are not the exclusive purview of engineering education. As chemistry spans science and engineering as defined by the Framework, many chemistry activities involve understanding and defining a problem and designing solutions. For example, most synthetic procedures are designs for a target molecule that solves a particular problem, and much of materials chemistry addresses the design of particular substances that have desired properties. Laboratory activities are more likely to incorporate such activities, and therefore, we developed new criteria for defining problems and designing solutions (Box 1). In addition, we developed criteria for communicating information, since that practice was also omitted from the 3D-LAP (Box 1). These new criteria were developed following a procedure similar to that used by the authors of the 3D-LAP (i.e., establishing/identifying criteria than an activity would need to satisfy in order to have the potential to elicit evidence that students are engaging in the practice).

Five authors independently coded both semesters of the project-based curriculum using the modified 3D-LAP criteria for scientific practices in constructed-response items and the additional criteria provided above (Box 1) for practices not included in the 3D-LAP. Each multiweek project was coded as a single unit. That is, all scaffolding provided by guiding planning questions and/or analysis questions for a particular project were considered as a whole, not as individual questions in isolation. For example, if a given laboratory activity asked students to create their own procedure to determine the relationship between absorbance and concentration and then asked the student to plot their data and construct an argument to hand in to their teaching assistant (TA), all prompts would be considered to be one unit of analysis, as none of these tasks is meant to be completed in isolation. Each practice for each experiment was treated as its own entity, giving a matrix of five raters by 81 items (nine practices for nine laboratory projects over two semesters of general chemistry laboratory). Inter-rater agreement between the five raters was calculated using pairwise percent agreement in Excel prior to discussion of discrepancies as was done with the 3D-LAP. Any discrepancies were discussed and resolved as a group so as to reach 100% agreement. None of the discrepancies changed any definitions from the 3D-LAP. 

Box 1. Additional Criteria for Practices Not Included in Three-Dimensional Learning Assessment Protocol (3D-LAP)

- **DEFINING PROBLEMS AND DESIGNING SOLUTIONS**

  Students are asked to design/build something to serve a function as a result of their investigation.

  1. Activity gives an event, observation, phenomenon, scenario, or model.
  2. Activity asks students to identify the findings from their investigation that will be used in designing the solution and how they will be used.
  3. Activity asks students to design or build a tangible product from the results of their investigation.
  4. Activity asks students to discuss how they weighed or prioritized competing criteria, such as function, feasibility in production of design, and/or cost, in designing the solution.

  For example, after investigating the conditions that control the rate of a chemical clock reaction, students design a one-time use chemical clock as a timer for a prescribed amount of time, or students design a glow-stick including packaging to meet specified parameters (duration of emission, color of emission, intensity of emission) after investigating a chemiluminescence reaction.

- **COMMUNICATING INFORMATION**

  Students are asked to present findings of their experiments to a nonexpert audience.

  1. Activity gives an event, observation, phenomenon, scenario, or model.
  2. Activity asks students to communicate their findings to an audience beyond the instructor in a way that could be understood by the general public.

  For example, students create a public health brochure about water contamination, a poster presentation for a superior about how a popular beverage color was recreated, or an oral report to the head of a recycling center on a separation scheme for recyclable plastics.
<table>
<thead>
<tr>
<th>Activity Component</th>
<th>Types of Questions/Prompts</th>
<th>Traditional Curriculum</th>
<th>Project-Based Curriculum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Procedure/Prelab</strong></td>
<td>• Prelab questions</td>
<td>1. Calculate how to make 10 mL of 3 dilute standards (0.147, 0.0980, and 0.0490 M) from the stock solution provided. The blue dye stock solution has been prepared to mimic a 0.245 M copper solution.</td>
<td>1. How will you use compounds of different colors to determine the relationship between the wavelength of light absorbed and the color?</td>
</tr>
<tr>
<td></td>
<td>• Questions about the procedure</td>
<td>2. Create a table in your lab notebook with columns for identity of the solution, volume of stock solution used, final concentration, and measured absorbance for each standard, the blank, and the malachite solution.</td>
<td>2. How will you use a solution of known concentration of one of the food dyes to determine the relationship between concentration and absorbance? Be sure to explain how you determined the wavelength for your analysis.</td>
</tr>
<tr>
<td></td>
<td>• Questions asked in the procedure section</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Guiding questions to help students design a procedure</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Data Manipulation/Analysis</strong></td>
<td>• Data analysis questions</td>
<td>1. Report the values and uncertainties for slope and intercept from the line equation produced by the spreadsheet.</td>
<td>1. What is the relationship between concentration and absorbance? Graphs may also help in this explanation.</td>
</tr>
<tr>
<td></td>
<td>• Prompt eliciting plotting/ displaying data</td>
<td>2. Write the regression equation using three significant figures for the slope and two significant figures for the y-intercept. Record the R² value.</td>
<td>2. How did you identify the dyes present and determine their concentrations? Include any necessary calculations.</td>
</tr>
<tr>
<td></td>
<td>• Instructions to perform calculations</td>
<td>3. Calculate the concentration (molarity) of the copper in your product using the absorbance of the malachite sample and the regression line above.</td>
<td>3. What is the relationship between the color of a compound and the wavelength(s) of light absorbed? Use your spectra to help support your conclusions.</td>
</tr>
<tr>
<td><strong>Discussion Questions/ Report Out</strong></td>
<td>• Prompts requiring students to synthesize data to reach a conclusion</td>
<td>1. Write a balanced equation including states of matter for the reaction of malachite with nitric acid. The products of the reaction are water, carbon dioxide, and aqueous copper(II) nitrate.</td>
<td>1. Provide a detailed analysis of the data collected and how it demonstrates that you created the same color profile as the original beverage.</td>
</tr>
<tr>
<td></td>
<td>• Prompts asking for claims supported by the data</td>
<td>2. It is possible that your malachite product is contaminated with copper(II) carbonate or some copper(II) oxide. The contaminants would change the percent copper by mass of your sample. You may assume your sample has malachite and only one contaminant. Based on the data provided and the results of your prior calculations, what can be deduced about the composition of your product?</td>
<td>2. Create (and present) a poster that outlines your team’s process, data, analysis, and findings.</td>
</tr>
<tr>
<td></td>
<td>• Postlab questions</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Discussion questions</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Prompts asking students to present findings via reports, posters, oral presentations, etc.</td>
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</tbody>
</table>
After the coding of the project-based laboratory projects, two of the authors followed the same procedure and coded together each of the laboratory activities from a traditional laboratory curriculum. Again, all tasks related with a particular investigation were considered as a single unit. The authors then performed a second round of coding on each of the project-based and traditional laboratory activities to determine which components of the activities (e.g., procedure/prelab tasks, data manipulation/analysis, discussion questions/report out) engaged students in particular practices. These components were closely related to the headings in their respective laboratory manuals. Examples of the types of prompts included in each component as well as specific examples from both curricula focusing on Beer’s Law are presented in Table 2.

Questions in the procedure/prelab component were questions or tasks that were asked of the students in the procedure section or any prelab questions they were asked to answer. For the project-based curriculum this included any prompts that students were provided to help them develop procedures for their investigations. The data manipulation/analysis component includes questions, prompts, or statements that ask students to analyze data they have collected, perform calculations, plot data points, or any other manipulation of data collected during the course of an experiment. Finally, the discussion questions/report out component encompass any questions, prompts, or statements that had students synthesize their data to reach a conclusion, make a claim about what they found, support their claim with evidence, answer postlab questions, or present their findings to a particular audience. The number of prompts in a given experiment was determined on the basis of the numbered or bulleted items in the student materials. If there was more than one question in an item within the number or bulleted list, it was counted as one prompt. For example, each numbered item in Table 2 would be considered as a prompt. Though data manipulation item 2 for the project-based curriculum asks for multiple things (determination of identity, concentration, and calculations), it was still just considered one prompt. The percentage of prompts in each component that engage students in a practice, or in part of a practice for a series of related prompts, was calculated. For example, if there were 10 prompts in the procedure/prelab component and three addressed or worked toward addressing a practice, the percentage of prompts would be 30%.

## RESULTS AND DISCUSSION

The results described herein represent 779 prompts across 24 traditional laboratory activities and 186 prompts across nine project-based laboratory activities.

**RQ 1: To What Extent Can We Reliably Characterize When the Scientific and Engineering Practices Are Present?**

Using the 3D-LAP SP criteria and the new criteria developed for those SP not covered in the 3D-LAP, we set out to identify the practices that students are prompted to engage in. The extent to which we can accurately characterize when practices are present and the nature of the practice is demonstrated by the average pairwise percent agreement between the 5 raters across all 81 items, which was 77.3%. The level of agreement between the raters is comparable to the inter-rater agreement observed in development of the 3D-LAP instrument, suggesting that the raters were understanding and using the coding scheme similarly in this work. This also exceeds the cutoff that the authors of the 3D-LAP established for acceptable agreement between raters in the development of the instrument. Having established inter-rater agreement with the project-based curriculum, two authors could progress to coding the traditional curriculum. To provide an example of how an individual project could address a number of practices, selected prompts that meet the criteria for practices are shown in Figure 1. In this figure, gray boxes represent those practices that are present in the project, while the white boxes represent practices that are absent.
Each of the prompts within the callouts taken together help to fulfill the criteria for a practice. The prompts do not necessarily appear in the same components of each activity, which is also why we coded the laboratory projects as a whole. For example, in the green callout (no. 3) for developing and using models, the first prompt is part of the prelab questions, while the second prompt is part of the discussion questions.

**RQ 2: To What Extent Are Scientific and Engineering Practices Explicitly Addressed in a Traditional and a Project-Based Curriculum?**

The final coding following reconciliation for practices in the traditional and project-based curricula is shown in Figure 2. The green shaded boxes indicate that a particular practice was included in the laboratory investigation, while the blue boxes in Project 3 of the first semester project-based curriculum (using math and designing solutions) represent practices that are included when the semester allows for the third week of the project to be done. Since there are two times more “experiments” in the traditional curriculum, only a representative sample of the laboratory activities from each semester are shown (Figure 2). A short description of all experiments in the traditional curriculum with coding for those not represented in Figure 2 and projects in the project-based curriculum can be found in the Supporting Information. Each laboratory activity has a unique “footprint” of practices that the students engage in. We can compare the “footprints” of the project-based laboratory curriculum to those from a traditional curriculum to investigate the differences.

From this coding, we can see that the investigations in the project-based curriculum incorporate multiple practices per investigation whereas the traditional investigations typically incorporate at most two practices per investigation. In the project-based curriculum, students are asked to design experimental procedures, collect and analyze data, and use the evidence to make claims about what they have determined in every project. Students are constantly asked to make sense of their calculations in light of the phenomenon studied, make changes to their procedures based on their findings, and carry out further experiments resulting from the changes to their procedures. In contrast, in the traditional lab students would seldom plan an investigation as detailed procedures are provided.

The traditional laboratory focuses on the practices that are most closely related to conducting confirmatory laboratory investigations (e.g., analyzing and interpreting data and using mathematics and computational thinking). This trend can be seen from the sampling of activities picked from both semesters, but it is also representative of all the of the activities in the traditional curriculum (see Supporting Information). Five of the 24 traditional laboratories address analyzing and interpreting data, and 11 of the 24 address math and computational thinking; there is only one laboratory activity that addresses both of these practices. Though one might argue that in any lab activity students should be analyzing data, using the 3D-LAP criteria, for a laboratory to be considered to engage a student in the practice of analyzing data it must meet the following criteria: students must (1) be given a scientific question, claim, or hypothesis to be investigated; (2) be given or construct a representation of the data; (3) provide an analysis of data; and (4) interpret the results or assess the validity of conclusions based on the question, claim, or hypothesis. The criterion that is often missing from laboratory experiments is the fourth, about interpreting the results or assessing the validity of the claims made in light of the data collected. This criterion could easily be added to existing laboratory experiments in order to fulfill the requirements for analyzing and interpreting data by asking...
students to comment on how their results fit in the context of the experiment. The practices of asking questions, defining problems/designing solutions, and communicating information were not addressed in any of the laboratories in the traditional curriculum. Recall that communicating information (Box 1) requires more than writing a laboratory report; students must engage in an activity that communicates their findings to an audience beyond the instructor.

In contrast, over the course of an entire semester of the project-based lab, students are engaging with each practice at least once (and at least three practices are found in every laboratory activity), giving students an opportunity to do the things that scientists do on a regular basis. For the first semester problem-based course, the practices found in every laboratory activity are planning and carrying out investigations, analyzing and interpreting data, and constructing explanations and engaging in argument from evidence. The second semester course has those practices plus mathematics and computational thinking and designing solutions. Neither of the curricula engaged students in all of the practices during a single project, which is reasonable given that scientists do not necessarily engage in every practice during a particular investigation.

The two curricula tacitly, but not explicitly, prioritize different learning goals. This is expressed through the tasks that students perform, giving rise to differences in the science practices in which students engage. The goals of the traditional laboratory appear to be focused on the procedure, the calculations, and the development of equipment manipulation.
skills, whereas the goals of the project-based laboratory are focused on the design of the procedure, and on analysis and interpretation of data, synthesis of results into a strong claim which is supported by evidence. In this way, students may develop ownership and agency over their laboratory learning that would be absent in the traditional course. In fact, Sandi-Urena\textsuperscript{22,23} has shown that some (but not all) students enrolled in such a course do develop an understanding of the goals of the course, and that “taking charge” is a theme that emerged from student interviews.

RQ 3. When Scientific and Engineering Practices Are Explicitly Addressed in a Laboratory Investigation, in What Parts of the Investigation (Procedure/Prelab, Data Manipulation/Analysis, Discussion Questions/Report Out) Do They Typically Appear?

To get a more detailed understanding of the workings of these two curricula, we examined the occurrences of practices within the three activity components. Using these components (procedure/prelab, data manipulation/analysis, and discussion/report out), the percentage of prompts within each component, for each activity, that address any practice was calculated. Further, the percentage of prompts associated with individual practices within each component, for each activity, was also calculated. If a prompt fulfilled or contributed to fulfilling a practice, it was considered to meet the criteria. For example, if one prompt asks for a calculation and the next prompt asks for an interpretation of the calculation in light of the phenomenon, both prompts are counted as contributing to fulfilling a practice. It is also possible that some prompts fulfill criteria for multiple practices; therefore, such prompts would be counted for both practices. For example, when students are asked to make a graph of data they have collected, this counts for both Criterion 2 for Analyzing and Interpreting Data (...gives or asks students to create a representation of the data to answer the question...) and Criterion 2 for Using Math and Computational Thinking (...asks students to... generate a mathematical representation...).\textsuperscript{19} The percentages of prompts in each component that address any practice are shown in Figure 3, and the further characterization of prompts by practice and by component is in Figure 4. The activities in these figures are the same activities from Figure 2. In Figure 4, orange diagonal stripes designate that 1–33% of prompts in that component address a practice; yellow vertical stripes designate that 34–66% of prompts in that component address a practice, and solid green designates 67–100% of prompts in that component address a practice. As mentioned, it is possible to have prompts that work toward fulfilling multiple practices, which means it is possible to have 67–100% of the prompts associated with more than one practice in Figure 4. The dark gray shading denotes components that were absent for a particular laboratory activity.

In Figure 3, the stark contrast is clear in the percentage of prompts that address any practice between the two curricula. The most notable difference is that the project-based curriculum has high percentages in all three components. This difference arises from the way in which questions/prompts are used between the two curricula. In the traditional curriculum, students are often prompted to calculate numbers in succession with little to no discussion between them about the implication or meaning of the results. For example, students could be prompted to calculate the concentration of Unknowns A, B, and C in three separate prompts. In contrast, as often happens with the project-based curriculum, students may be asked for a calculation in one prompt, in the next asked to compare their calculation to a known value, and then in a final prompt asked to comment on how they may change their procedure on the basis of their results. While none of these prompts fulfills a practice on their own and they all work to fulfill different practices, the sum total of the prompts together addresses a broader goal.

From Figure 4, the more fine-grained analysis by practice gives us further insight into the structure of these curricula. In the traditional curriculum, the prompts that engage students in practices predominantly appear in the Discussion/Report Out component. What this suggests is that students are largely working through procedures without being required to fully engage in the scientific practices. When students in the traditional curriculum do engage in the practices, the most prevalent practice is mathematical and computational thinking; they complete the calculations and answer the discussion questions, which may often occur outside of class time without direct support of the instructor. In contrast, the practices are interspersed throughout the three components of the project-based laboratories. However, in many cases, specific practices are most frequently associated with particular components of the laboratory activity. A summary of which practices were commonly found in the components can be found in Table 3.

<table>
<thead>
<tr>
<th>Lab Activity Component</th>
<th>Most Common in Traditional Curriculum</th>
<th>Most Common in Project-Based Curriculum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Procedure/Prelab</td>
<td>Using math and computational thinking</td>
<td>Planning and carrying out investigations; Asking questions</td>
</tr>
<tr>
<td>Data Manipulation/</td>
<td>Analyzing and interpreting data</td>
<td>Developing and using models; Analyzing and interpreting data; Using math and computational thinking</td>
</tr>
<tr>
<td>Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discussion Questions/</td>
<td>Using math and computational thinking: Developing and using models</td>
<td>Constructing explanations and engaging in argument from evidence; Communicate information</td>
</tr>
<tr>
<td>Report Out</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Common Practices by Lab Activity Component
presentation). Engaging in the scientific practices while students are in class gives time for the instructor to provide guidance and support as the students work through their projects.

The analysis provided here further emphasizes how the two curricula will result in different outcomes. The traditional curriculum tends to emphasize following correct, provided procedures for both experimental setup and data analysis to arrive at a correct, predetermined answer as a result of the experiment, which is reflective of the early goals of chemistry laboratories to train technicians.1,2 The project-based curriculum’s focus on students collaboratively working to solve a problem or design a solution requires students to plan, monitor, and evaluate their own work; that is, they are asked to engage in metacognitive activities very much like a practicing scientist.2,25 It also places much more emphasis on the process of science, with less emphasis on getting the correct answer. When an experiment does not work as expected due to a flawed experimental plan or inadequacies in execution, it provides students with the opportunity to reflect on the source of the unexpected result and then adjust accordingly. This could be either through reflecting on their existing experimental design and looking for areas to improve, devising a new experimental plan, or repeating the experiment if the original plan is judged to be sound. All of these mirror the work of practicing scientists. It is also important to note at this point that the goals of a particular laboratory course may be influenced by the student population enrolled, for example, a chemistry class for engineering majors, which may also constitute an emphasis on particular practices over others.

CONCLUSIONS

We have demonstrated that, by using the modified Three-Dimensional Learning Assessment Protocol (3D-LAP),30 it is possible to reliably determine whether the potential to engage students with specific scientific practices is present in a laboratory activity. Further, we have demonstrated that using scaffolded prompts, providing additional authentic report-out mechanisms (poster presentations, oral reports), and guiding students in development of their own procedures as seen in the project-based laboratory curriculum have the potential to engage students in a wider range of scientific practices. The characterization of laboratory activities can also be used to compare and contrast curricula with respect to their potential to engage students in scientific practices. Changing the unit of analysis from whole laboratory activities/projects to components of the activities/projects revealed that in traditional laboratories, when practices were present, they were most often found in the procedure or discussion components, whereas the project-based laboratories incorporated practices throughout each component of the activity/project, though some practices tended to be found primarily in particular components, such as planning and carrying out investigations in the procedure component and constructing explanations in the Report Out/Discussion component.

IMPLICATIONS, LIMITATIONS, AND FUTURE WORK

Not only can the modified 3D-LAP be used to characterize current laboratory activities as shown here, but also it has the potential to guide the design of laboratory learning experiences by providing the criteria that should be met to elicit a given practice. We believe that this approach may also be useful in characterizing the activities that are required of students in other reformed laboratory curricula, for example, CUREs. By applying the modified 3D-LAP to CUREs, we may be able to compare different types of laboratory curricula with CUREs. Currently, CUREs are largely compared with traditional laboratory activities. If CUREs have science practice “footprints” more like the project-based curricula, then it is not surprising that they would yield different student outcomes as it not an equal comparison. However, an analysis, such as the one we have described here, could support the identification of comparable CURE and project-based laboratory programs allowing more equitable comparisons of student outcomes to be made.

Further, the characterization of a more traditional curriculum, as discussed here, can provide an important first step for those looking to reform their laboratory curriculum and incorporate revisions designed to help students engage in more of the scientific practices. This is the benefit of using such explicit criteria, like those from the 3D-LAP, as these give concrete ways in which materials can be revised to give students the chance to engage in scientific practices before, during, and after the laboratory period. For example, adding a question prompting students to think about how their result compares with a published value and why their number may be different (analyzing and interpreting data) would give the student the potential to engage in a practice. If a fully transformed curriculum is not feasible, through using the criteria for the scientific practices, an instructor could incorporate a few practices of interest into a curriculum to work on with students that would benefit them as they continue through their chemistry sequence.

The potential to elicit scientific practices before, during, and after a laboratory activity does not guarantee that students will actually learn to use them, nor does it speak to the quality of prompts that are used to elicit the practices as we know that the wording of a prompt for students has great implications for what a student can and will demonstrate.31–35 What is still needed is the ability to assess how these different types of curricula affect students’ understanding and use of the practices. While there are a number of instruments intended to assess content outcomes, attitudinal changes, and prowess with particular scientific practices (e.g., argumentation) as the result of laboratory curricula, currently there are few ways to assess learning outcomes in terms of the larger variety of scientific practices as defined by the Framework. It should be noted, however, that our current study also does not speak to whether students are proficient with the practices as there currently are no assessment approaches that would allow us to measure such proficiency. The future work of the project team is to develop assessment tasks to determine student proficiency with scientific practices. Such tasks will allow us to investigate under what circumstances students develop proficiency and whether different laboratory programs (including CUREs) promote different levels of proficiency.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.8b00912.

Codings for scientific practices for all projects/experiments in both semesters of both curricula, with a brief...
description for each project/experiment describing what the students do in the laboratory and the goals intended for students to accomplish. (PDF, DOCX)

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Notes

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