A Study of the Literature on Lab-Based Instruction in Biology

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Abstract

We analyzed the practitioner literature on lab-based instruction in biology in The American Biology Teacher *between 2007 and 2012. We investigated what laboratory learning looks like in biology classrooms, what topics are addressed, what instructional methods and activities are described, and what is being learned about student outcomes. The practitioner literature reveals a focus on novel and innovative labs, and gaps in some biology topics. There is little description of student learning, but motivation and engagement are a primary concern of authors. There is little evidence of students addressing the nature of science in laboratories, and too few opportunities for authentic exploration of phenomena. We suggest that biology instruction can be strengthened by more rigorous practitioner research through increased professional collaboration between teachers and education researchers, increased focus on the synergy between content and teaching practice, and more rigor in reporting student outcomes.*

Key Words: *Lab-based instruction; inquiry; science practices; research collaboration; student learning.*

○ Introduction

The *Next Generation Science Standards* (NGSS) emphasize the importance of science and engineering practices as well as content knowledge (NGSS Lead States, 2013). Science practices are embodied in laboratory experiences – defined by the National Research Council (NRC) as lessons in which students are "interacting directly with the material world or with data drawn from the material world" (NRC, 2006, p. 78), whether in the classroom, the computer lab, or the field. Laboratory experiences defined thus are a key part of students' developing scientific ability and understanding (Latour, 2013).

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The design and implementation of lab curricula has been the subject of much discussion, and professional development, over the past several decades (e.g., Schwab, 1962; DeBoer, 1991; Janovy, 2003; NRC, 2012). However, there has been remarkably little basic research on the efficacy of lab experiences (NRC, 2006). Furthermore, a chronic disconnect between education research and teaching has limited the implementation of successful lab practices (Monk & Osborne, 2000). One part of the disconnect is the lack of research that captures and tests the knowledge of expert science teachers – moving knowledge from practice to research. This is an additional obstacle to incorporating the best lab experiences into science learning (NRC, 2006, 2012).

Here, we look at the existing literature on lab practices in biology education in the practitioner literature represented in *The American Biology Teacher* (*ABT*). The research literature on lab-based learning experiences in all domains of science reports the kinds of intellectual work that students do in labs (Millar et al., 2000; Monk & Osborne, 2000; Drayton & Falk, 2001); the kinds of activities related to sense-making – data analysis, model building, or argumentation and reasoning – that are expected of students (Driver et al., 2000); and, sometimes, the learning outcomes that result (NRC, 2006; Drayton et al., 2013).

In a recent review of findings in the research literature on lab instruction in biology over the past 20 years (Drayton et al., 2013), we found a high prevalence of papers reporting on student content knowledge, reasoning, and motivation/engagement outcomes, and a low prevalence of student understanding of the nature of science, change in attitudes about science, and classroom participation. In labs ranging from kindergarten through college freshman levels, we found few studies in which students addressed the nature of science within the lab context. Few inquiry-based labs were described in which students themselves formulate a question; there were slightly more labs in which students direct the investigation design; most prevalent were labs in which students directed their sense-making (including discussion, argumentation, and connecting results to theory). There was a high prevalence of labs with living materials (e.g., dissections) and computer models (e.g., Daisyworld simulations), and a low prevalence of field-based labs

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(e.g., a field trip to a local stream) or physical models (e.g., a plaster skeleton). The most common activities within the labs were student observation, data gathering, and data analysis. Least common were experimentation, argumentation, and building/evaluating models. Ecology and genetics labs are frequently studied, whereas physiology, molecular biology, and microbiology labs are not. Researchers focused most on high school, and less on middle school and university levels. There was little reporting on outcomes or designs for populations of interest (e.g., underserved populations, English-language learners). Finally, the review revealed a strong innovation bias, with researchers focusing on novel interventions instead of common or standard curricula. The research questions we address here, shaped by these findings, are as follows:

1. What are the basic characteristics of *ABT* articles (e.g., background of authors, student demographics and grade level, subject matter)?
2. What does the practitioner literature in *ABT* tell us about how pedagogy is enacted in the classroom, including inquiry-based instruction and instruction on the nature of science?
3. To what extent does the practitioner literature in *ABT* report on the efficacy of lab-based instruction? That is, to what extent are student outcomes reported, and what types?

Our goal in conducting the study was to indicate where additional research and documentation might productively be focused, and to begin to address the continuing disconnect between education research and practice (Lagemann, 1997; Monk & Osborne, 2000). In particular, answers to our research questions might have implications for both improved teaching and improved learning, including professional development, and illuminate what expert teaching looks like.

○ Methods

We examined K–13 lab experiences described in *ABT* articles published between 2007 and 2012. Having found 347 articles initially, we excluded articles that did not meet the following criteria:

1. Biology teaching or learning was the focus, as opposed to a context for studying something else (e.g., cooperative learning or expository writing). We excluded 16 articles on the basis of this criterion.
2. The lab fit the NRC's characterization of a laboratory experience, which defined a lab experience broadly as student engagement with living material in classroom, lab, or field or with data drawn from the real world, such as population counts or data on plant growth rates (NRC, 2006, p. 78ff). We excluded 131 articles on the basis of this criterion.
3. There is some evidence that the lab had been implemented in the classroom (e.g., a report of student outcomes, or use of the past tense in describing implementation). We excluded 89 articles on the basis of this criterion.

The coding rubric consisted of 28 coding constructs, a definition of each, and examples from the literature to illustrate them. See Drayton et al. (2013) for the complete coding rubric. We coded basic information about each article, including research methodology (e.g., mixed methods, observational), domain of biology, instructional purpose, classroom activity structure (e.g., demonstration, argumentation, exploration), type of material studied (e.g., field, living organisms or parts of organisms, multimedia), degree of inquiry (coded as level of student responsibility taken for lab question, lab design, or sense-making from lab), and student outcomes.

Our final study corpus of practitioner literature included 111 studies. Two researchers coded all articles; inter-rater reliability was 87%. Where disagreements occurred, coders discussed the differences and established an agreed coding.

○ Results

Here, we describe (1) the basic characteristics of the articles (author, school level, subject matter); (2) the instructional purpose of the labs, as well as the activities students engage with in the labs and how they engage with them; and (3) the level of reporting of student outcomes. In all figures, articles could be coded in more than one category.

Basic Characteristics

Authors. Although, on the basis of our prior work, we had expected the practitioner literature to originate in the K–12 classroom, we found that a high percentage of *ABT* articles were authored by college faculty alone (Table 1). Just under a third were authored by K–12 classroom teachers. Faculty authors frequently noted that their rationale for writing was to share with teachers a novel and/or innovative lab that worked well with their freshman students.

School level. High school was the most frequently reported level in the *ABT* literature, followed by introductory university classes and middle school (Table 2). No articles focused on elementary school, while a small percentage of the studies included mixed grades.

Demographic variables. Only 12% included any information on student demographics other than grade level, a gap that was also present in the research literature.

Subject matter. Ecology was the most common topic in both bodies of literature, followed by genetics. However, there were major differences in the relative importance of several of the other domains (Figure 1). The low incidence of evolution, molecular biology, and human biology or behavior topics in the *ABT* articles may reflect the preponderance of articles about high school and college introductory courses, since these domains are more likely to be addressed at these levels.

Table 1. Representation of author professions.

K–12 Teacher	Scientist	Professor	Education Researcher	More Than One Type	Not Described/ Other
33%	40%	42%	14%	37%	18%

Table 2. Representation of grade levels.

Elementary	Middle	High	University	Multilevel	Not Described
0%	9%	43%	30%	9%	9%

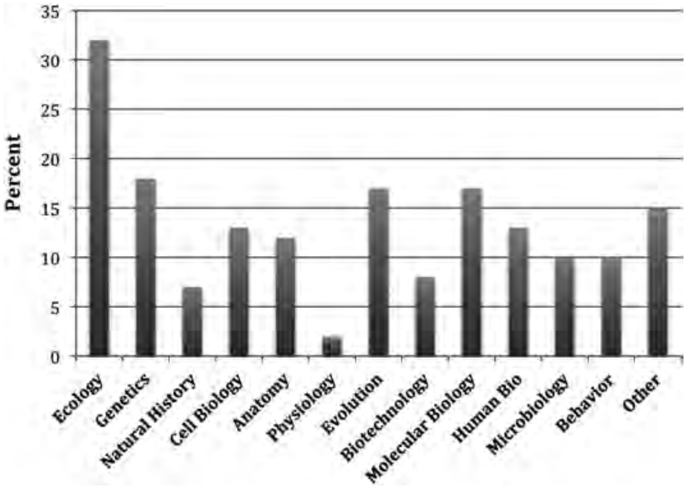

Figure 1. Representation of biology domains in the *ABT* literature.

Pedagogy & Student Activities

Innovation bias. Few common or standard labs were examined, not even to test their efficacy, whether studied alone or compared to an innovative approach. Rather, the goal of almost all (94%) of the articles was to describe novel lab experiences.

Instructional purpose. A large majority of the *ABT* studies (92%) reported teaching new concepts as one of the instructional purposes. Learning "manipulative or experimental techniques" (25%) or "analytic techniques" (49%) were the next most common. Only 21% were designed to engage students in an "exploratory hands-on activity" to familiarize them with organisms or systems. This is perhaps related to the fact that no articles were focused on elementary labs, and only 9% on middle school labs, at which levels instruction tends to be more focused on experiential learning through exploration.

Lab materials and activities. Students in the *ABT* articles engaged with living or prepared biological material (e.g., tissue samples, slide preparations) in two-thirds of the labs (66%), but only 13% of the labs were focused on field systems (e.g., trips to local streams, observing insects on schoolgrounds) (Figure 2). This could reflect limited time and logistical difficulties of getting students out of the classroom. Students engaged in observing, exploring, and gathering observational data in most (85%) of the *ABT* articles, but these activities tended not to be explicitly described as having an instructional purpose. Students analyzed data in 75% of the studies and engaged in argumentation in just over half (56%).

A much higher percentage of physical models than computer models was represented. This could reflect limited technology access in schools. Providing an opportunity for students to engage with complex data was an explicit feature of many of the computer simulations, with the stated purpose of supporting students in making and justifying inferences. Active engagement in making models is one way in which students can investigate the underlying value and use of a technique or a concept. However, even in labs in which students build models (qualitative or quantitative), most only follow a set procedure to engage with the model, while few actually engage in analyzing it (Figures 2 and 3). Forty-four of the articles reported engaging students in quantitative activities such as data analysis.

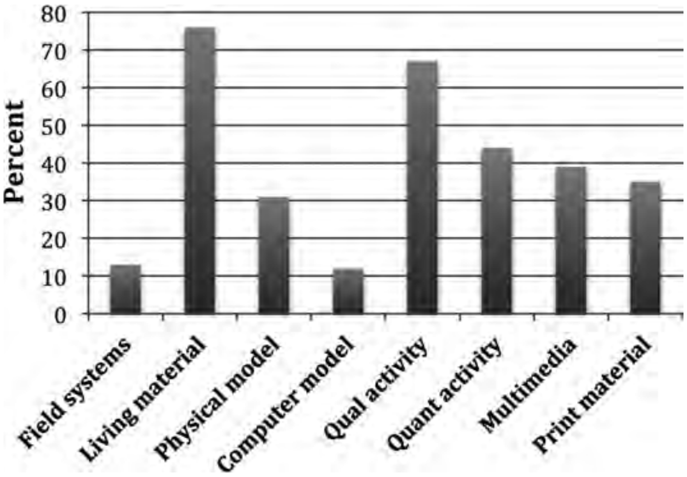

Figure 2. Materials that students used during lab activities (%).

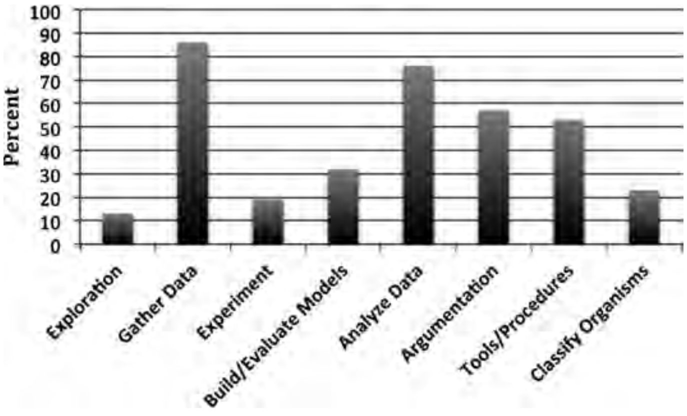

Figure 3. Types of lab activities (%) designed to meet the described instructional purposes.

In sum, the *ABT* literature emphasizes student activities that involve gathering of observational data, data analysis, and student argumentation in service of sense-making.

Nature of Science (NOS). NOS (Abd-El-Khalick, 2013) rarely appeared as a component of student lab activities (Figure 4). Although 29% of articles showed students directly addressing processes or practices of science, only 3% were focused on NOS as part of the lab as well. This may be because NOS is typically taught as a separate topic; to address this possibility, we looked at the *ABT* articles we had excluded from the study because biology was not the focus of the article but the context for another topic – in this case, NOS. We found 17 articles focused on NOS, which suggests the possibility that teachers are indeed addressing the nature of science as a separate topic that is not integrated into laboratory experiences.

Degree of inquiry. To characterize inquiry, we asked whether students or teachers directed the process of (1) selecting the investigation question ("question formation"), (2) choosing investigation and data analysis methods ("investigation design"), and (3) making sense of lab outcomes ("sense-making"). Indicators for these aspects of inquiry included, but were not limited to, indeterminate outcomes (as opposed to a predetermined "right answer"), descriptions of teacher "surprise" (at the direction student sense-making took), and mention

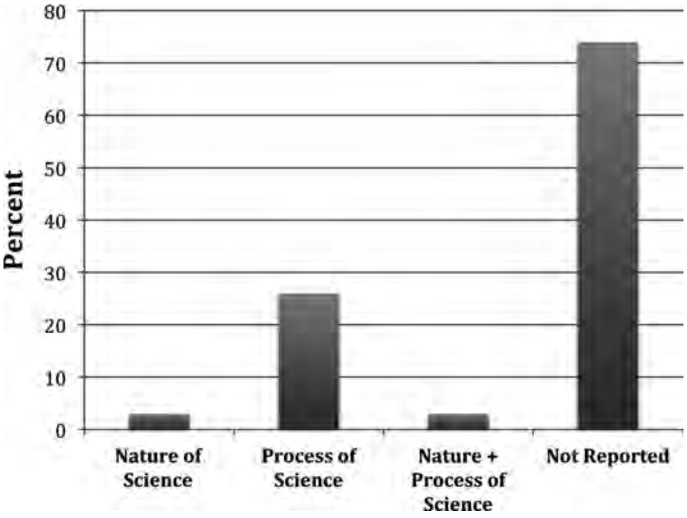

Figure 4. Representation (%) of science practices and nature of science.

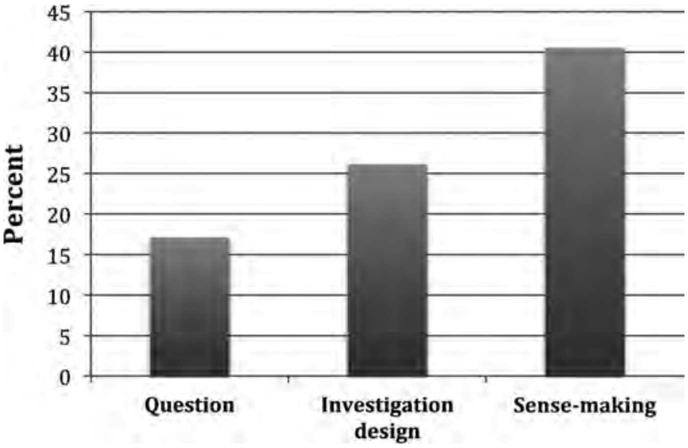

Figure 5. Representation (%) of levels of student-directed inquiry for each of the inquiry measures shown.

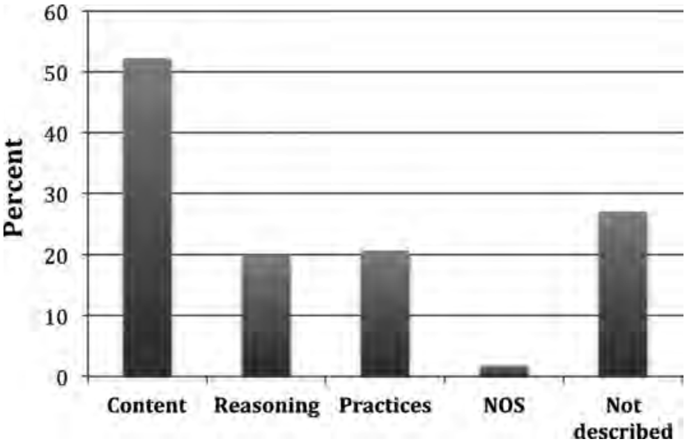

Figure 6. Percent frequency of reporting on learning outcomes for students.

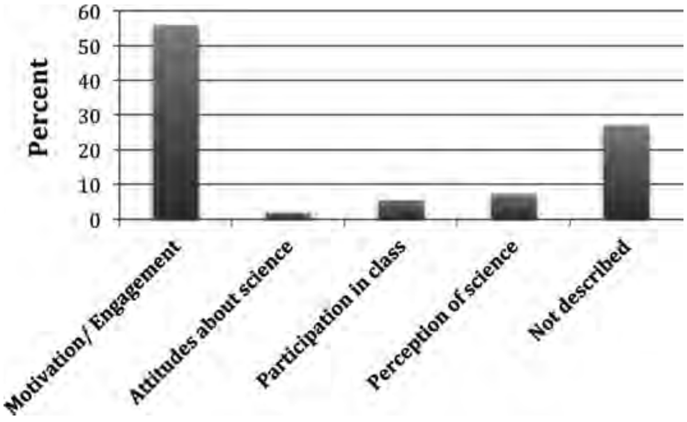

Figure 7. Percent frequency of reporting on affective outcomes for students.

of "independent student research" as evidence of student-directed inquiry. As Minner et al. (2010) and others have noted, it is often difficult to discern the level of inquiry from the frequently inadequate level of detail provided by authors.

The teacher was responsible for question formation in 83% of the articles (i.e., the inverse of the data shown), and for investigation design in nearly three-quarters (74%) (Figure 5). Levels of student-directed sense-making are higher (60%), showing that authors most valued student responsibility for knowledge construction. Thirty percent reported a teacher-directed sense-making process, while a further 10% did not describe student sense-making at all. Only 11% of articles showed student responsibility for all three categories of inquiry.

Inquiry in longer labs. One much-discussed obstacle to student-directed inquiry is time pressure (Key & Owens, 2013). We found that when students directed question formation, labs were almost 4× as likely to be extended over several class periods compared to when students did not (53% vs. 14%). Student-directed investigation design and sense-making were less time-demanding; 34% of labs with student-directed investigation design were extended, compared with 16% of labs with teacher-directed investigation design. Student-directed sense-making demanded almost no extra time (29% vs. 20%), perhaps indicating that labs included limited options for divergent outcomes even when the sense-making component was student-directed.

Student Outcomes

Over a quarter of the articles (27%) did not describe student outcomes, while another one-fifth (20%) described only one. Instead, authors focused the narrative almost entirely on procedure. Content learning was the most frequently reported outcome, while knowledge of the nature of science was rarely reported (Figure 6). Just over one-third (36%) of *ABT* articles used any sort of systematic study of student outcomes. Those that did included qualitative data like transcripts or surveys, quantitative data like test scores, and (rarely) experimental design of intervention and control groups. Two thirds (64%) of the articles reported only informal observations of the student experience, tending to focus the narrative almost entirely on the lab procedure instead.

Student motivation or engagement were the most frequently reported affective outcomes (Figure 7). In fact, authors often gave student motivation or engagement as the explicit rationale for writing about a novel lab experience. These results suggest that practitioners find that motivating and engaging their students is their primary concern.

○ Discussion

The findings of our study confirm the disconnect between education research and practice (Lagemann, 1997; Monk & Osborne, 2000) and indicate where additional research and documentation can productively be focused. The trends we found have implications for improved teaching and learning – namely, including inquiry-based activities (especially at higher grade levels), a need for research on commonly taught labs in addition to novel ones, and a need to include explicit focus on student outcomes.

Implications for Improved Teaching & Learning

Increased student engagement in inquiry activities. Almost 40% of *ABT* authors asserted in their introductions that "inquiry" was the instructional method used, often referencing national standards, techniques such as the "5 E's," and "constructivist learning" as justification. In addition, they often explicitly contrasted this with standard learning techniques by referencing "cookbook" labs. However, just half of these authors presented any evidence of inquiry in their lab descriptions, at least as defined by our codes. This finding supports observations by other *ABT* authors (Gottfried et al., 1993; Eastwell & MacKenzie, 2009; Richardson et al., 2012) that authors often talk about inquiry practice but do not provide evidence of implementation. These results may reflect the assumption by authors that they do not need to describe inquiry because *ABT* readers know how to teach via inquiry, or that authors are simply using the descriptor "inquiry" to refer to student sense-making – which is just one part of inquiry-based instruction – as a favored alternative to direct instruction.

Although many articles mentioned an effort to teach an inquiry-based curriculum, few gave evidence of active student engagement in inquiry. Student-directed inquiry is a difficult practice to implement and has been the focus of education research for decades. Efforts should be made to escape the "cookbook" approach by reflecting upon what dimensions of inquiry are actually incorporated in lab activities in practice. Are students provided the opportunity to pose their own questions? Do they get any experience designing their own investigations? If they are expected to construct their own understanding, is the expectation one of narrow and specific concept understanding, or is it one of integration with broader biological concepts? These questions are especially salient because of the shift from "inquiry" to "science practices" in the most recent standards (NGSS Lead States, 2013). Although the science practices described in the NGSS include defining questions and designing experiments, they do not place an emphasis on student *responsibility* for these practices, along with the concomitant pedagogical practices that entails. A teacher may assume that her students are engaged in inquiry by engaging in science practices, but this is not enough to develop a strong understanding of the process of inquiry. Although NGSS hopes to put students in more control of their own learning in the classroom, we worry that the emphasis shift from "inquiry" to "practices" will diminish the already low level of student-directed inquiry reported in biology labs. Given teachers' priorities for their own professional development (described below), readers of *ABT* are likely to need more detail about how to implement student-directed inquiry.

Increased focus on the nature of science in laboratory experiences. Only a few papers describe labs that present opportunities for student reflection on the process of science as a theory-driven enterprise. Research has shown that inquiry practice alone does not lead to increased constructivist beliefs or a better understanding of scientific epistemology (Lederman et al., 1998). Research in inquiry science emphasizes teaching both *with* and *about* the nature of science – it may not be sufficient to teach decontextualized lessons on the nature of science (Abd-El-Khalick, 2013). Labs are an ideal venue for calling attention to how particular kinds of biology are done, for example in discussing the specifics of a lab procedure or during lab reporting. Evidence from the *ABT* literature points to a missed opportunity to integrate critical reflection alongside science practices.

Inquiry science need not be a time sink. Currently, student-directed inquiry represents a time trade-off for teachers who are struggling with content standards that limit the time available for in-depth learning (Sandoval & Reiser, 2004; Key & Owens, 2013). Sacrifices in content material are often proposed as a method for increased student learning (e.g., Sundberg et al., 1994). However, the research literature indicates that implementing a curriculum focused on student-directed inquiry does not necessarily demand additional classroom time, and supports the argument that inquiry experiences need not combat the requirements of state standards for content.

Increased exploration in older grades. Exploration is a key stage of inquiry; without this process, students cannot direct an authentic process of hypothesis formation. The practitioner literature shows a low prevalence of "exploratory hands-on activities" for older grades. This indicates that older students are not given the opportunity to explore phenomena before being expected to develop higher-order hypotheses and tests for them. For example, despite the heavy focus on ecology labs, few articles showed students engaging with field systems, the obvious laboratory material for exploring complex systems. Only 45% of ecology laboratories used either field systems or computer simulations. Even in urban schools, ecological questions can be explored in the field.

Exploration plays a key role in the growth of biological expertise. Biological scientists build disciplinary insight from their rich experience with phenomena; students need to engage in this practice too. By enhancing students' knowledge of biological phenomena at an organismal and a system level, exploration lays the groundwork for deeper questions and more meaningful interpretations.

Increased synergy between content and pedagogy. Most of the articles in our study provided little description of student learning as a result of the lab. Most articles in *ABT* are written to introduce new activities and seem to focus more exclusively on lab procedure. A consistent challenge in teaching science is the synergy between content and pedagogy (Abell, 2008). Indeed, National Science Foundation data on teacher priorities in professional development show that only 24% of teachers rate content as the main priority for professional development: the other 76% prioritize pedagogical and school-climate issues (National Science Foundation, 2012). Teachers should receive more integrated training on how labs are enacted in classrooms to support student-directed inquiry (Key & Owens, 2013).

Implications for Improved Professional Collaboration

Research and practice. Scientists, education researchers, and classroom science teachers can be a source of collaboration for the development of effective, engaging science learning experiences. However, few *ABT* articles were collaborations between researchers and practitioners; 14% of articles written by K–12 teachers had an education researcher on the author team, while 3% of college professors had an education researcher on the author team. On the other hand, 45% of K–12 teachers had a scientist on the author team, indicating that teachers are more likely to be collaborating with scientists than with education researchers. This is perhaps a result of the NSF guidelines that scientists use some of their funding on community outreach, whereas there are fewer "required" opportunities for education researchers to collaborate with teachers involved in the process. On the other side of the triangle, there is a strong history of collaboration between scientists and education researchers as well (NRC, 2012). This is represented in the *ABT* articles: 56% of articles written by an education researcher were in collaboration with a scientist. Given the challenges around integrating pedagogy and content, the collaboration between teachers and education researchers seems the most important to foster, moving forward. On the other hand, the literature may reflect a bias on the part of education researchers to publish their results in academic research journals. Our findings suggest that they might productively bridge the research–practice divide by publishing in practitioner journals as well.

Increased research on common labs and underrepresented science topics. The results of our study indicate that there is incomplete knowledge of how standard labs are taught and how effective they are (at least in the period covered by this review) and that the majority of student experiences remain unexamined by practitioners. Increased analysis of standard labs – for instance, critique of misconceptions embedded in commonly used models (e.g., Milne, 2008) – is necessary to fully describe the range of student laboratory experiences in biology. Increased analysis of underrepresented science topics such as microbiology and molecular biology will also help capture expertise on how to teach these topics through labs.

Increased consensus around the meaning of "inquiry." As already discussed, our results show little evidence of student-directed inquiry, even in articles that explicitly put forward labs as inquiry based. We found that "inquiry" was interpreted broadly and described with little detail. This may be a lack of consistency in writing or in actual classroom implementation. If the lack is the result of authors not describing practices that are, in fact, already happening in the classroom, the articles risk perpetuating confusion around the meaning of inquiry (Eastwell & MacKenzie, 2009). However, if the lack reflects labs in which student-directed inquiry is not happening, this means that many classrooms are not engaging students in ways that expert teachers, researchers, and scientists hope to foster (Enyedy & Goldberg, 2004). As "practices" shift to the forefront with implementation of the NGSS, productive collaboration depends on our ability to be precise in how we describe practices, in how we implement instruction around practices, and in how we provide rigorous evidence of what inquiry really looks like in the classroom.

***Increased description of student learning and experience in* ABT.** The *ABT* articles focused mostly on procedure, with little description – even informally – of student learning or outcomes. Twenty-seven percent described no student outcomes, and another 20% described only one outcome, most often motivation and engagement. This lack suggests that authors write for *ABT* to provide detail on what to teach in a novel lab, and assume that readers take it on faith that the lab has positive outcomes.

We recommend that *ABT* authors pay more attention to describing student learning and other student outcomes, whether formal or informal. This will allow better evaluation of the effectiveness of interventions, create a more detailed record of methods in the classroom, and help capture existing teacher expertise. These are data that the NRC has noted are missing from the literature (NRC, 2006), and data that will help us understand the role of labs in biology instruction. We note that such a focus may also correct our finding about the lack of student-directed inquiry, if authors are recording not only how to teach a lab but also how students are enacting the lab and what they learn from it. Finally, only 30% of the articles had a K–12 teacher on the author team; most were written by people whose primary professional training was in a science domain. Increased collaboration between education researchers and teachers could provide more comprehensive measures of student experience, instead of focusing on only one part of the student outcome data.

Our results confirm that the practitioner literature can explore frontiers in biology education. If practitioners take our suggestions – for example, to increase their reporting on student outcomes and describe the efficacy of standard, as well as novel, lab instruction – they can enhance rigorous knowledge about the role and value of labs in biology education.

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