The Nature of the Teacher's Role in Supporting Student Investigations in Middle and High School Science Classrooms: Creating and Participating in a Community of Practice

A Commissioned Paper for the National Academies of Sciences, Engineering, and Medicine's Committee on Science Investigations and Engineering Design for Grades 6-12.

December 1, 2017

Matthew Kloser
University of Notre Dame
mkloser@nd.edu

This paper was commissioned for the committee on Science Investigations and Engineering Design for Grades 6-12. The committee was convened by the Board on Science Education in Washington, DC with support from the Amgen Foundation and the Carnegie Corporation of New York. Opinions and statements included in the paper are solely those of the individual author, and are not necessarily adopted, endorsed, or verified as accurate by the Board on Science Education or the National Academy of Sciences, Engineering, and Medicine.

Investigations are central to the scientific enterprise. Nobel Laureate and theoretical physicist, Max Planck, described an experimental investigation, as "a question which science poses to nature, and [the] measurement [as] the recording of nature's answer" (Planck, 1949). Unfortunately, school science has often failed to engage students in the dialogue between science and nature, producing instead a "rhetoric of conclusions" (Schwab, 1962, p. 24) or "final form science" (Duschl, 1990) in which students may know about particular topics, but not how they are justified. Even when teachers engage students in material activity, criticisms have been levied against "cookbook" tasks in which students follow a given set of procedures like a recipe, failing to make connections between the discrete steps of the procedure and the larger question at play (Brownell & Kloser, 2015; Germann, Haskins, & Auls, 1996; Windschitl, Thompson, & Braaten, 2008).

This paper addresses the roles that teachers must play in middle and high school science classrooms to effectively engage students in investigations that raise questions in students' minds, unveil the exciting, often messy, and negotiated enterprise we call science, and help students better understand both what and how we know about natural phenomena. In moving students beyond a "rhetoric of conclusions" and toward a more three-dimensional science learning experience (National Research Council, 2012), teachers play an integral and complex role. For some teachers, this role is made more difficult by confusion within the field about such conflated terms as labs, inquiry, and investigations. Furthermore, many science teachers' own experiences have been "cookbook" in nature, experiences exacerbated by organizational and institutional constraints that can prevent their on-going development in facilitating effective investigations.

Drawing on the conceptual and empirical literature, this paper argues that while multiple models for investigations exist that align with a three-dimensional framework of science education, each model places at its center the necessity for the teacher to create a community of practice within the classroom. The paper is organized into three main sections. The first section clarifies similarities and differences among the often-conflated concepts of inquiry, labs, and investigations. The second section – the central focus of this paper – frames the teacher's role as an expert embedded within a community of practice. This section identifies key elements of an investigative community and highlights several existing models. Finally, the third section outlines the needs for preparing pre- and in-service teachers to facilitate investigations in light of this framework.

Clarifying constructs: Inquiry, labs, and investigations

Inquiry: A historical driving force in science education

Over the past several decades, traditional, expository forms of instruction have been eschewed for school science conducted as inquiry. The *National Science Education Standards* (National Research Council, 1996) define scientific inquiry as "the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work" (p. 23). The standards further define that learning *through* inquiry occurs when students are actively engaged in understanding important scientific concepts and developing competencies in how scientists inquire about the natural world. More recent conceptual frameworks, like the *Framework for K-12 Science Education* (National Research Council, 2012) and the *Next Generation Science Standards* (NGSS Lead States, 2013), also highlight the importance of students developing

This paper was commissioned for the committee on Science Investigations and Engineering Design for Grades 6-12. The committee was convened by the Board on Science Education in Washington, DC with support from the Amgen Foundation and the Carnegie Corporation of New York. Opinions and statements included in the paper are solely those of the individual author, and are not necessarily adopted, endorsed, or verified as accurate by the Board on Science Education or the National Academy of Sciences, Engineering, and Medicine.

competencies to explore the natural world, but these current frameworks articulate more specific goals for science education than a 'science education as inquiry' lens provides. The three-dimensional science instructional approach is a means for young people to:

> [Have] some appreciation of the beauty and wonder of science; posses sufficient knowledge of science and engineering to engage in public discussions on related issues; [be] careful consumers of scientific and technological information related to their everyday lives; [be] able to continue to learn about science outside school; and have the skills to enter careers of their choice, including careers in science, engineering, and technology (National Research Council, 2012, p. 1).

These goals require not only an understanding of how scientists study the natural world, but also an understanding of how young people can participate authentically in this enterprise.

Despite good intentions, confusion still exists about what constitutes effective inquiry (Crawford, 2014; Furtak, Seidel, Iverson, & Briggs, 2012), thus limiting its potential to create classroom environments in which core disciplinary ideas, crosscutting concepts, and scientific practices work in concert to help young people achieve the goals of science education. For example, inquiry sometimes has been conflated with any hands-on experience. But as the American Association for the Advancement of Science (1993) commented almost twenty-five years ago, hands-on activities do not necessarily result in meaningful experiences that help students engage in the conceptual, epistemic, and social aspects of science. Furthermore, inquiry has been described not as a single construct but rather as a continuum that ranges from confirmatory activities that are teacher-led and traditional in nature to discovery-based and student-led tasks (Banchi & Bell, 2008; Furtak et al., 2012; Schwab, 1962).

Dozens of studies have compared the outcomes of different types of science classroom interactions, often comparing various forms of inquiry-based instruction to traditional science classroom contexts. In one quasi-experimental, matched pairs study of undergraduate freshman not far removed from their high school experience, students who engaged in "cookbook-type" activities in which they were given the research question and procedures for a known outcome – a hands-on experience, but not necessarily one involving much inquiry – had statistically worse attitudes toward, lower self-confidence in doing, and decreased interest in pursuing biological research when compared to a teacher-guided, authentic research lab experience (Brownell, Kloser, Fukami, & Shavelson, 2012). Similarly, in a randomized controlled trial, teacher-guided inquiry was related to a higher impact on student achievement when compared to more traditional forms of science teaching (Wilson, Taylor, Kowalski, & Carlson, 2009). In this study, sixty students were randomly assigned to either an inquiry-focused unit based on the 5E instructional model (Bybee, 1997) or a unit based on commonplace teaching practices as identified in a survey of American science teaching (Weiss, Pasley, Smith, Banilower, & Heck, 2003). Controlling for pre-test scores, the authors showed that students in the inquiry group scored significantly higher on the post-test than students in the control group, with a relatively small effective size of .27. However, on items that pressed students for higher-level reasoning, such as model-based accounts, students in the inquiry-based condition scored significantly higher with an effect size of .42.

Another longitudinal study followed 74 middle school science teachers engaged in inquiry-based professional development over a five-year period. Nearly 10,000 students within their classrooms, hailing from diverse backgrounds, showed statistically higher achievement, but small effect sizes, on science practices and concepts as assessed by the adaptive NWEA MAP test, compared to students in non-participating teachers' classes (Marshall & Alston, 2014). Previous studies of the professional development experience provided for the teachers in the treatment condition indicated shifts in the participating teachers' practice toward a stronger inquiry focus as measured by the validated EQUIP and RTOP instruments (Marshall, Smart, Lotter, and Sirbu, 2011), suggesting that the teachers' pedagogical approach was at least partly responsible for the growth. Furthermore, the pre-existing achievement gap between Caucasian students and students from non-dominant populations decreased in the treatment condition, but not in the control condition.

A meta-analysis, drawing on 37 experimental or quasi-experimental studies comparing inquiry and more traditional modes of science learning reflect similar results across the literature (Furtak et al., 2012). Culling research from 1996 – 2006 that measured the effects of inquiry teaching on students' cognitive outcomes, the authors report a general effect size of .50. These findings were slightly lower than Schroeder et al's (2007) older, but similar, meta-analysis of experimental and quasi-experimental studies that found an effect size of .65 in favor of inquiry teaching.

Furtak and colleagues further disaggregated their results based on Duschl's (2008) three-part framework for science education – inquiry attending to conceptual structures (e.g. drawing on prior knowledge or providing conceptual feedback), inquiry attending to epistemic frameworks (e.g. drawing conclusions based on evidence or generating and revising theories), and inquiry attending to social interactions (e.g. participating in class discussions or giving presentations) – as well as a fourth category focused on the procedural tasks of asking questions, designing experiments, and creating data representations. These categories were compared to control conditions that lacked different combinations of these elements. The authors found that the largest effects occurred when epistemic elements were included in the treatment (d_{mean}=.75) and when procedural, epistemic, and social elements were combined as part of the treatment (d_{mean}=.72). Other combinations of the four categories showed only small effect sizes ($\leq$ .24). Comparisons also were made based on the level of guidance provided to students during inquiry. The ten studies that compared teacher-led inquiry versus traditional science instruction reported a medium effect size of .65 while student-led inquiry reported a much smaller effect size at .25, when compared to traditional instruction.

Differentiating inquiry, labs, and investigations

The data above suggest that inquiry positively affects student outcomes. Inquiry teaching is present in American classrooms, but according to 2007 TIMSS data, inquiry exists less frequently than didactic, teacher-centered approaches or approaches that are heavily textbook and worksheet driven (Gao & Wang, 2016). Even among teachers who have adopted an "inquiry approach", confusion can arise. As defined in the original national science education standards, inquiry can represent both the manner in which scientists make evidence-based claims about the world and the manner in which science learning can occur in middle and high school classrooms (National Research Council, 1996). These multiple understandings of "inquiry" make difficult the work of defining the teacher's role in facilitating investigations in a three-dimensional science classroom. The ambiguity that continues to surround the term 'inquiry', as well as its multiple meanings, dilutes the usefulness of the term. Furthermore, the inquiry continuum includes a broad range of interactions (or lack thereof) that can further puzzle teachers about their role. For example, students may engage in inquiry through historical case studies or the comparison of different texts without engaging in material activity or data collection. To avoid confusion, this paper refers to inquiry in terms of the pedagogical approach by which students in middle school and high school classrooms can learn core ideas and develop competency in scientific practices. Meanwhile, laboratory activities (labs) and investigations represent different constructs that fall under this broad, umbrella term of inquiry. The following sections highlight the differences between labs and investigations as operationalized in this paper.

America's Lab Report (National Research Council, 2005) defines labs as "opportunities for students to interact directly with the material world (or with data drawn from the material world) using the tools, data collection techniques, models, and theories of science" (p. 31). The report further clarifies the types of activities that are included in this definition, such as chemistry experiments, computerized models and simulations, remote access to instrumentation, or the analysis of large databases. Based on this definition, labs can play an important and educative role in the science classroom. They can be used to understand discrete ideas like the relationship between force, mass, and acceleration on a dynamics cart or the density of different objects by floating (or sinking) them in known liquids. However, as Windschitl (2017) notes, lab activities typically limit the decisions that students can make about what and how ideas are explored and often times remain disconnected from on-going sensemaking about core disciplinary ideas. Although a bit dated, findings from Driver and colleagues (Driver, Leach, Millar, & Scott, 1996) indicate that students who engage extensively in isolated, highly structured labs, fail to see the connections between the findings from these labs and more in-depth models of science ideas.

In contrast, investigations as articulated not least by the *Framework*, are part of an on-going *system* of exploration and material activity that address central disciplinary concepts that cannot be fully understood within one or two 50-minute periods. Investigations are embedded within systems of activity, discussion, and reflection (Windschitl, 2017). Singular lab activities can contribute to broader investigations, but only if the labs have purpose, connect to previous ideas, and help build on more refined theories of how the world works. While traditional cookbook "labs" might engage students in a known question, with known best procedures, and a known best answer, high-quality investigations are "problematic" while helping students construct new science ideas (Duschl and Bybee, 2014). "Problematic" scientific work involves and *desires* struggle on the part of students to make sense of the world – to know that just asking a question does not always lead to a clean, "right" answer.

Having differentiated between labs and investigations, the focus of the paper turns toward better understanding the teacher's role. In trying to distinguish among inquiry, labs, and investigations, the misconception may arise that the role of the teacher is to open up the lab and stay out of students' way as students discover the wonders of the world around them. While three-dimensional science learning is student-*centered*, drawing on their ideas and engaging them actively in the practices of science, it is not necessarily student-*led*. In fact, Furtak and colleagues' (2012) findings from a meta-analysis highlight the important role of the teacher. They found a sizeable difference in effect sizes when teachers (d_{mean}=.65) led the inquiry process compared to when students (d_{mean}=.24) led the process.

Teachers play many roles in inquiry classrooms including: "motivator, diagnostician, guide, innovator, experimenter, researcher, modeler, mentor, collaborator, and learner" (Crawford, 2000). But teacher education and professional development that must focus individually on each of these roles would like prove overwhelming. As cognitive load theory posits, individuals that are faced with multiple demands, such as the many roles that teachers are asked to play in classrooms, benefit greatly from focusing their attention on a limited set of practices as they develop expertise (Van Gog, Ericsson, Rikers, & Paas, 2005). Therefore, rather than articulating each discrete skill or role that a teacher must play in the classroom, science teachers' ultimate role in facilitating investigations is to create a community of scientific practice. The following section decomposes the central parts of any community of practice in light of scientific investigations and provides several existing models in which teachers can create and guide such a community.

Creating a Community of Practice: Scientific Investigations

Communities of Practice: Essential Elements

Practice, as defined by Wenger (1998), "[is] a process by which we can experience the world and our engagement with it as meaningful" (p. 51). Practice gives meaning and structure to what we do – in the case of science investigations, practice includes the norms, roles, tools, language, criteria for participation, and goals of activity for students and teachers to make meaning of the natural and material world (Chaiklin & Lave, 1996). A community of practice consists of the social interactions and learning that occurs when people have a common interest or pursue a common goal collaboratively over an extended period of time. In Wenger's (1998) seminal book on communities of practice, he notes that the elements of practice give meaning to the community that is gathered. Even more powerfully he notes that participation in a community of practice goes beyond "mere engagement" (p. 57). Rather, participation is something carried with participants; it is not something that is "turned off". Cookbook "lab" activities are often contained within the classroom and any accompanying homework. Students follow a given procedure, often without questioning its rationale. They gather data without meaningfully contextualizing or discussing their findings with other members of the classroom. And when they leave the classroom, they leave the activity behind. In contrast, within a community of practice students develop different science identities that are not limited to a single activity. Students are prepared to engage in scientific practices not only within the classroom experience, but also outside of the classroom because they have developed stronger science identities. Given recent research on the importance of science identities and STEM persistence, especially for underrepresented populations in STEM (Andersen & Ward, 2014), the formation of a community of practice may have long-lasting effects beyond the school walls.

A community of practice consists of three essential components: 1) mutual engagement (a community); 2) joint enterprise (a domain); and 3) a shared repertoire (defined practice) (Wenger, 1998). The following section briefly defines each of these elements in terms of how it relates to school based science investigations and the subsequent sections discuss the role of the teacher in shaping each essential element.

First, mutual engagement suggests that members of the community are working together. Mutual *engagement* goes beyond mutual *participation* because members of the community negotiate what science ideas to explore, define investigative norms, and share practices. Experts – most often the teacher – may provide guidance to novices – most often the students – but the voice and ideas of all the members are central to the work. Mutual engagement is critical, therefore, to pursue what an emerging literature has labeled as "ambitious science teaching" (Thompson, Windschitl, & Braaten, 2013) in which students' ideas are central to instruction. In traditional labs, pairs of students often conduct the same procedure, collect the same data, and write the same lab report. While participating in common activities, this type of work would not qualify as mutual engagement because the students are all doing the same job with little to no negotiation or classroom level interactions with each others' ideas.

Second, communities of practice are centered on a joint enterprise. Members negotiate "what counts" as work within the community, resulting in mutual accountability for each other's practice. In science laboratories, the joint enterprise or domain might include the investigation of a particular protein and its physiological effects as well as the epistemic foundations for these investigations. In school science, the domain is centered on a series of core disciplinary ideas that define earth, life, and physical science and the scientific epistemology that is tied to the crosscutting concepts and scientific practices. Teachers and students must engage in the practices of science as well as the crosscutting concepts to understand not only what we know, but how we know it (Duschl, 2008).

Third, teachers and students share practice. In this community, teachers and students develop a shared repertoire of resources, tools, and ways of handling problems. Importantly, participants *develop* these repertoires, they do not just learn about them in the abstract. Thus, students must be participants in the epistemic elements of investigations as well as the conceptual. Teachers play a significant role in providing approximations for students to develop routines and ways of solving problems, often through the enactment of core instructional practices (Ball & Forzani, 2009; M. Kloser, 2014) or the use of tools (Windschitl, Thompson, Braaten, & Stroupe, 2012), both of which will be addressed below.

Justifying a Community of Practice Lens for Science Investigations

Why attempt to define classroom-based science investigations as actors participating in a community of practice? Three reasons are most salient. First, literature from diverse disciplines such as the history, philosophy, and sociology of science portray science less as an individual, expert pursuit resulting in unbiased claims and more as a network of actors at varying levels of expertise, both within an individual lab, but also within the broader scientific community. The idea of science, and therefore scientific investigations, as a community of practice has precedent from multiple disciplines. Philosophers of science like Kuhn (1962) have alluded to interactions in which rules are not handed down as immutable truths, but rather negotiated socially amongst its participants. Similarly, Longino's (1990) feminist philosophy of science highlights the community as the source of science's objectivity since individuals bring latent and explicit biases and error to their work. A sociological study of a laboratory analyzed the interactions of scientists as they worked to construct facts, indicating that the process was highly social and negotiated (Latour & Woolgar, 1986).

Of course, the purpose of school science is not to replicate solely what occurs in a scientific lab. What can be replicated, however, is the development of, engagement in, and reflection on how the community investigates the natural world to construct knowledge – sometimes new knowledge, but more often new knowledge for students that can be attached to meaningful contexts. Existing notions of what "counts" as science stand in contrast to the position of investigations as *social* practice. For example, results from fifty years of the "Draw-a-Scientist" study indicate that students even at a young age perceive scientists as isolated individuals working in their lab (Finson, 2002).

This paper was commissioned for the committee on Science Investigations and Engineering Design for Grades 6-12. The committee was convened by the Board on Science Education in Washington, DC with support from the Amgen Foundation and the Carnegie Corporation of New York. Opinions and statements included in the paper are solely those of the individual author, and are not necessarily adopted, endorsed, or verified as accurate by the Board on Science Education or the National Academy of Sciences, Engineering, and Medicine.

And a quick accounting of the prestigious, Intel International Science and Engineering Fair shows that although students were allowed to work collaboratively, only 9% of the 450 winners chose to do so (Wilsey & Kloser, 2015). This is problematic because working individually does not prepare students for actually engaging in the community of science and engineering practice and it weakens the final knowledge claims and products.

Second, a dichotomy is established too often that pits a "teacher-centered" focus against a "student-centered" focus for classifying investigations. Taber (2010) notes that these distinctions may not be useful. Investigations should not be defined by the central player, but rather by the interactions that occur between teachers and students. This viewpoint emphasizes that members of a community of practice exercise different roles when needed to meet the goals and objectives of the community, in this case, to better understand core disciplinary ideas, how they are justified, and why they are important. This community of practice may be the best reflection of what actually occurs in science while allowing the teacher to maintain roles necessary to helping students achieve the goals of the *Framework for K-12 Science Education*.

Third, and finally, the framing of investigations as a community of practice better reflects what we know about how people learn. From a sociocultural lens (Vygotsky, 1978), students working within a community who develop common language and construct collective understanding through interactions can draw on larger stores of prior knowledge, be exposed to diverse viewpoints and ideas, and challenge exiting assumptions. Among others, Chi's (2009) meta-analysis suggests that, on average, interactive environments result in better learning outcomes for students.

Identifying Roles in the Science Community of Practice

Communities are comprised of participants who bring different attributes to the joint venture and who fill different roles. Although naïve understandings of science may expect all participants in labs or field studies to be experts in their field, communities of practice include a range of novices, emerging experts, and experts. So too, within a scientific classroom community of practice. The teacher generally plays the role of the expert, helping students who enter the community at varying levels of expertise (including differences in conceptual, procedural, epistemic, and social knowledge) to enter more fully into the work of the community. In an authentic science laboratory, the PI serves in many different roles: administrator, questioner, author, quality control manager, and facilitator of material activity. Teachers fill these same roles when facilitating science investigations, plus they must manage elements unique to classrooms such as behavior. As mentioned previously, focusing training on even a small number of these roles could be overwhelming, given the limited time teachers spend in pre- and in-service training. But thinking about the work not as a series of discrete roles, but as the expert within a community of practice who seeks to 1) create a shared community, 2) help identify the joint enterprise, and 3) support students' development of a repertoire of practice can result in more connected and learnable roles for the teacher.

The Teacher's Role in Creating a Shared Community

Communities of practice operate within a set of established norms. In the science classroom, teachers establish norms that guide general behaviors – how students interact physically in groups or socially through talk (Magnusson, Palincsar, & Templin, 2004). Concurrently, the teacher must also build a community focused on disciplinary norms. These disciplinary norms cut across many scientific practices and include the types of questions that science does and does not explore, how evidence is privileged when making and supporting claims, and how the community helps monitor the quality and accuracy of findings.

Communities of practice use language as an important tool for reaching specified goals. Having established collaborative norms, teachers must also help facilitate discussion that occurs at the small and whole group level. Scientific talk has been promoted for several decades as a major means for improving students' sensemaking of core science ideas (e.g. Lemke, 1990). However, not all talk is productive as not all talk moves both individuals and the community toward greater understanding of the natural world. As a Delphi panel of science education researchers and science education practitioners identified, perhaps one of the most important roles of the teacher is to facilitate discourse in ways that draw on students' ideas, attend to existing theories and evidence to shape those ideas, and equitably promote uptake of students' ideas amongst each other (Kloser, 2014).

The core or high-leverage instructional practice[1] of facilitating discussion requires that teachers build a community in which ideas are respected and used collectively. Traditional I-R-E questioning formats occur when teachers initiate (I) interaction by asking an individual student a question followed by the student's response (R) and the teacher's evaluation (E) of that response. This questioning pattern often fails to address the needs of the entire learning community. Unfortunately, as one study of 188 teachers, 22 of whom taught science, showed, approximately 50% of all questions were closed, I-R-E type probes while only about 20% of questions were open in nature and required an extended answer (Bergman & Morphew, 2014). Recent work focused on the role of the teacher in facilitating discussion across multiple subjects conducted by a multi-institutional consortium (Core Practice Consortium, 2017) has targeted four key elements to facilitating productive talk: 1) framing the discussion; 2) facilitating the talk; 3) representing ideas; and 4) closing the discussion.

In framing discussions, the teacher revisits the norms for how the community will interact (Michaels & O'Connor, 2017). Do students need to raise their hand or can they monitor their own turn taking? How can students respectfully engage other students' ideas even when disagreement arises? Furthermore, the teacher explicitly identifies the goal for discussion – is the community eliciting a range of ideas based on prior knowledge or is the community using evidence from material activity to construct or refine models (Kloser, Wilsey, Madkins, & Windschitl, in press)?

After the discussion is framed, the next two components – facilitating the talk and representing ideas publically – occur synchronously and iteratively. When facilitating science talk, the teacher's goal is to foster uptake of students' ideas. Uptake occurs when a student puts forth an idea and other students address that idea instead of offering a new one. This engagement in others'

---

[1] Confusion may arise from the diverse use of the word practice throughout this paper. Social practice is associated with the work of communities as defined by sociologists like Reckwitz (2002) and others. Scientific practices often refer to a more specific set of practices used to investigate the natural world. The *Framework* and *NGSS* draw upon eight such scientific practices. And finally, core instructional practices, also called "high-leverage" practices in some of the literature, refers to those elements of *teaching* that can be identified and used flexibly to help students reach the relevant disciplinary goals. To differentiate, I use the descriptor "scientific" or "instructional" when relevant.

ideas more-often results in negotiated ideas and better-supported claims. Teachers and students often draw on social tools, such as the productive talk moves described below, that push for clarification and elaboration, allow students to agree or disagree with an idea, and privilege evidence over opinion (Chin, 2007). These talk moves indicate to the community that all members want to understand each others' thinking (Michaels & O'Connor, 2017). Importantly, when engaging in this type of discussion, teachers should provide students enough time to think and avoid evaluative responses. Rather than acknowledge the "correct" nature of a response, teachers can use phrases like, "Interesting idea, who else would like to talk about that idea?" (Michaels & O'Connor, 2017).

Concurrently, teachers must make decisions about what ideas to represent publically. This includes the selecting of student work such as drawn models or graphs of data from an investigation as well as the scribing of ideas on the board (Cartier, Smith, Stein, & Ross, 2013; Windschitl et al., 2012). Here, the teacher's role is not to capture *all* ideas, but rather to represent ideas that have been collectively agreed upon by students and move the community toward the learning goal. This element of instructional practice has also been shown to be supported by the use of various tools, such as a "summary table", described below (Kloser et al., in press).

Facilitating productive talk can move forward not only disciplinary goals, but also equity goals if teachers recognize the extra supports that students from non-dominant communities may need. Establishing an environment in which all students' voices are respected and in which students are encouraged and taught how to respectfully engage each others' ideas can shift the power dynamic in traditional classrooms from the teacher as the source of knowledge to the students bringing knowledge from their own backgrounds (Moll, Amanti, Neff, & Gonzalez, 1992) or from material activity or conceptual models. However, merely helping students recognize the primary features of scientific discourse patterns will not help students from non-dominant populations fully participate if their native discourse patterns are totally neglected or if they cannot use scientific language in meaningful contexts (Michaels et al., 2017).

When conducting investigations within a community of practice, students' own language resources as well as scientific discourses can be drawn upon to help students construct explanations or models about scientific phenomena (Brown & Kloser, 2009). McNeill and Pimentel (2010) compare three case studies in urban environments in which discussion and argumentation are infused. They highlight the differences observed in the teachers' roles across the classrooms, only one of which included student-to-student interactions. The teacher who fostered student-to-student interactions used more open-ended questions and allowed students to use both scientific and everyday language. By recognizing students' ideas and their language resources, this teacher encouraged the community to consider new ideas and reflect on thinking from their classmates. In another case study investigating how a high school science teacher engaged 54 students in science argumentation, almost half of which were English Language Learners (ELLs), three instructional strategies were observed that supported students' engagement in the community of practice. First, the teacher validated the use of the students' primary language to ensure they could conceptually understand the core science ideas. Many students would speak in Spanish during pair and small group work before translating the ideas to English. Second, the teacher provided deliberate scaffolds such as expectations that each claim should be supported by two pieces of evidence. Finally, the teacher used small group work prior to whole-class discussion in order to provide ELLs the opportunity to share their ideas in low-pressure situations.

This work, of course, is difficult and unnatural for many teachers. In a case study in which a project-based investigative approach was used amongst a classroom community, 97% of whom were African-American students, teachers were prepared to lead productive and equitable discussions. In practice, they reverted to traditional IRE-type patterns (Alozie, Moje, & Krajcik, 2010). The authors suggest that several structures could better help teachers realize their role in leading classroom discussions. These structures centered on curriculum guides that could provide more rationale for planned discussions, a set of open-ended questions that teachers could use, strategies for training young people to engage in discussion, and strategies for facilitating and not dominating discussions, especially for students unaccustomed to this type of discourse.

The Teacher's Role in Defining the Joint Enterprise of Scientific Investigations

The purpose of science in research labs and field studies is to generate new knowledge and construct theories by which the world is understood. Previous writings have suggested that it is important to distinguish authentic science from school science because the latter seeks to help students understand existing knowledge and theories (Crawford, 2014). If thinking only about labs – single activities that help address known knowledge – this would be true. However, investigations as defined in this paper require on-going question asking, development and testing of models, and the capturing of data to support or disprove these models centered on core disciplinary ideas. When contextualized and situated, investigations can help students learn and use old knowledge to explain or model previously unseen phenomena. Thus, the role of the teacher in helping define the joint enterprise is to identify a contextualized phenomenon or a central, anchoring question tied to a core disciplinary idea that promotes questions among students and the opportunity to address these questions in various ways (Krajcik & Czerniak, 2014; Windschitl et al., 2008).

Contextualized problems relate to students' interests or personal lives. These problems, often framed as questions, must be "worthwhile, feasible, grounded in real-world problems, and meaningful" (Krajcik, McNeill, & Reiser, 2008, p. 8). Krajcik (2015) proposed several ways in which teachers can identify worthy phenomena or central questions including, drawing ideas from the local environment and context (e.g. relationships in local habitats or ecosystems), tapping into students' hobbies (e.g. skiing or skateboarding), identifying current challenges that face the environment (e.g. global warming), or drawing on scientific issues posed by accessible scientists or the media. The difficulty, of course, is ensuring that the phenomenon in question addresses appropriate standards.

Focusing on phenomena embedded with one or more core ideas is a cornerstone of a community of practice. Communities of practice work toward a joint enterprise that is negotiated (Wenger, 1998). The foci of traditional labs rarely are negotiated; the teacher often has a particular idea to be addressed, and in the case of cookbook labs, the protocol only addresses that idea with a constrained procedure. Next generation science learning is a negotiation. As Schwarz and colleagues (Schwarz, Passmore, & Reiser, 2017) outline in their set of steps to organize sense-making, the teacher and students have to identify, "What are we trying to figure out?" (p. 15). This question begets some level of negotiation that, using the anchoring phenomenon, elicits students' questions and initial ideas. Furthermore, the focus on complex and sometimes "messy" phenomena has equity implications. Relevant, contextualized experiences connect underrepresented populations in STEM and English learners to the science community (Tolbert, Stoddart, Lyon, & Solãs, 2014).

The Teacher's Role in Developing a Repertoire of Practice with Students

Helping students develop a repertoire of practice addresses the second two questions posed by Schwarz, Passmore, and Reiser (2017) that teachers must support when facilitating investigations: How will we figure it out? and How do we keep track of what we are figuring out? In helping students plan and carry out investigations focused on core disciplinary ideas, Krajcik and Czerniak (2014) frame the teacher's role as a targeted questioner that helps students do four important tasks: identify variables, define variables operationally, control variables, and write clear procedures. In helping students address these four components of scientific practice, the teacher must also provide opportunities for the community to critique and provide feedback on the research designs. The authors also note that short, albeit artificial, exercises of critiquing a host of existing research designs for a particular question can provide students opportunities to think critically about the quality of an investigation and what procedures can produce the most valid data that addresses the question at hand.

Using Conceptual and Social Tools to Facilitate Investigations

Helping students develop a repertoire of planning investigations or engaging in argument from evidence can be significantly aided by the introduction of tools. Teachers may need to introduce students to physical tools used throughout investigations. Microscopes enable students to observe and gather data from the unseen world. Sensors and probeware allow for more efficient and precise data collection of constructs such as pH, acceleration, or water oxygen levels. Computer hardware and software provide simulations of phenomena that may otherwise be too difficult to manipulate because of scale. Indeed, a Delphi panel identifying core instructional practices (Kloser, 2014) cited the managing of materials and lab equipment as an important aspect of science teachers' practice.

However, the managing of or introduction of physical tools to students generally requires just skill. In contrast, helping students engage in a shared community of scientific practice requires attention to goals, knowledge, skills, and norms. For many teachers, being taught or observing core instructional practices, such as facilitating sensemaking discussions about data, does not necessarily translate into high-quality instruction. Conceptual and social tools can help teachers move limited instructional practice toward more expert enactments. As Windschitl et al. (2012) suggests, tools play a "critical role [for teachers] when a set of practices is shared within a community of novices and teacher educators" (p. 880). Tools can provide a bridge between existing levels of expertise and the goal of a given task. Hence, tools may be critically important not only for novices within teacher education, but also for all science educators. The impact of tools has been shown empirically in a variety of ways. In one study that followed novice middle and high school science teachers from methods courses to rehearsals of facilitating a sensemaking discussion with peers to facilitating a sensemaking discussion with students, novices who had been taught to use a discussion tool called a "summary table" to publically represent students' ideas were more likely to represent collective findings from students and discriminate between utterances that were useful in moving the discussion forward than teachers who were not introduced to this tool (Kloser, Wilsey, Madkins, & Windschitl, in press).

Conceptual and social tools represent non-tangible scaffolds that directly address students' engagement in three-dimensional science learning. One example of a conceptual tool is a teacher's prompt for students to think about a phenomenon or an investigative encounter "with microscope eyes" (Davis et al., 2017). Introducing this tool could occur in the context of constructing models within an investigation in which students must be pushed to think about the causal mechanisms by which the observed events occur. Other structures such as investigative prompts can serve as tools for teachers' facilitation. One such heuristic, suggested by Windshitl, Braaten, and Thompson (2008), pushes students beyond addressing the outcomes of an investigation and focuses them on explaining how variables might relate in a given circumstance. Rather than asking "If [we observe or manipulate these conditions] then [we should observe this outcome]", they promote asking, "If we believe that [these relationships within our model are accurate, then when we [observe or test under these conditions] we should observe [these outcomes]" (p. 18).

Similarly, social tools might include structured and recurring ways in which students and teachers interact throughout an investigation and help them accomplish a task more effectively. While discussing data across groups to make claims about observations or causal events, students might be prompted to use a set of productive talk moves (Cartier et al., 2013; Chin, 2007). These tools provide structure for discussants to press each other for evidence-supported claims, ask for clarification, and agree or disagree with ideas respectfully.

In describing their set of four core instructional practices that frame science teaching, Windschitl et al. (2012) altered their vision of practice-based teacher education because of their observations of how tools were necessary to mediate elements taught in the methods courses and classroom practice. Face-to-face tools were central to novice teachers' elicitation and representation of students' ideas. Novices developed iterations of how students could represent models, whether it was a three-panel drawing of a before-during-after event or individual ways for students to represent causal explanations. Other face-to-face tools fostered social interactions such as "thought-tracker" sentence starters that helped bridge students' ideas coming out of experiences with material activity and academic scientific language. Similarly, "back-pocket questions" were developed by teachers to address students' increasingly complex levels of thinking about a phenomenon or investigation. The authors also detail a case study in which one novice teacher used a face-to-face tool that helped move the class toward collective understanding. This tool, the "summary table", is a four-column table in which major observations, patterns, and sensemaking about material activity is collected. The teacher facilitates discussions about each column and then asks the class how these ideas should be publically represented. Students can keep their own versions of the summary table in their notebooks and this tool helps scaffold revisions to previously drawn models.

The authors argue that the presence of core instructional practices are more likely to achieve their goals of eliciting and building students' ideas about causal phenomena when mediated by conceptual and social tools. Of note, they detail the importance of providing tools that have flexibility – even novices were found to adapt existing or create new versions of tools to their classroom context and the unit of focus (Windschitl et al., 2012). Furthermore, the authors note that the presence of the core practices and the introduction of common tools allowed for novices to grow professionally together. That is, they had created their own community of practice centered on practice-based science instruction. Thus, tools will likely play a key role in helping teachers develop competency in the core instructional practice of facilitating investigations that are three-dimensional in nature.

The above discussion of tools focused on Windschitl et al.'s (2012) research on face-to-face tools. Their work also identifies the importance of what they call "Priming Tools". Priming tools provide teachers opportunities to think critically about the nature of the curricular focus and sequence. A three-dimensional approach to science teaching suggests that students are moving away from coverage of a broad set of science topics (e.g. forces, water cycle, or volcanoes) and toward core disciplinary ideas that have causal stories and predictive power for understanding how the world works. Both full units and investigations can benefit from tools that foster the type of reflection and structure observed by priming tools. As noted above, traditional lab tasks have been criticized for their overemphasis on procedural activity that is disconnected from a conceptual framework or does not help student thinking advance toward causal explanations or revised scientific models. Research on the Science Writing Heuristic (SWH) (Putti, 2011) provides an example of one tool that can help prime and facilitate teachers' and students' interactions within a scientific community of practice that is focused on three dimensional learning.

The SWH is a tool that authentically involves students in the investigative experience. While one author has described the SWH as "an alternative method of writing lab reports" (Putti, 2011, p. 516), others have investigated the SWH as a tool for shifting the existing paradigm of school-based investigations (Hand, Wallace, & Yang, 2004). Hand and colleagues' writing pre-dates the introduction of the *Framework* (National Research Council, 2012), but their description reflects the tool's potential in fostering three-dimensional science learning as part of a community of practice.

The SWH process begins with a pre-lab discussion in which students bring investigative questions about the core idea and write them on the board. Unlike traditional cookbook tasks or lab reports in which students write down a given question, students are provided sentence starters that ask, "What do I want to know about ____?" or "How does ___ relate to or depend on ___?" (Putti, 2011, p. 517). A student facilitates the discussion as the class decides on a question for exploration and generates a data table. The teacher plays the role of the expert, recognizing where students do and do not need extra support and alignment to the key standards of the unit. For some investigations that are technically advanced, the teacher provides a set of procedures and discusses the rationale for these procedures with students. In other cases, students have the opportunity to form procedures themselves. Following data collection, students post their data electronically so that the class community has access to all of the results. The teacher then facilitates a post-lab discussion in which students engage in the crosscutting concept of pattern-finding among the data. The discussion helps students answer the question, "Based on my observations, what am I trying to claim?" (Putti, 2011, p. 518). Students then use evidence to justify their claims and reflect on their learning.

As mentioned above, while students have an active role in deciding the orientation of the investigation as well as carrying out the investigation, the teacher has important roles throughout the SWH process. The teacher must first elicit students' thinking about the unit's core ideas in order to shape investigative opportunities for exploration. While students take ownership in the early stages of the investigation, the teacher monitors equipment needs and helps groups gather valid data. Upon data collection, the role of the teacher increases as they facilitate four consecutive "negotiations" – 1) the teacher tailors individual writing prompts for students to negotiate their own understanding of the data; 2) the teacher orchestrates group discussion about the data and presses for possible claims from the data; 3) the teacher identifies and provides additional resources that can help further student understanding about their claims and enable students to make connections between the material activity and more general concepts; and 4) the teacher again develops individual writing prompts that help students consolidate their thinking.

This writing heuristic, when focused on core ideas, provides classroom communities the opportunity to engage in three-dimensional learning precisely because it is housed within a community of practice. The initial prompts help students move beyond superficial data collection and toward understanding causal relationships that can then be tied to broader theories in the negotiation stages. Crosscutting concepts and a variety of scientific practices are iteratively present as the expert – the teacher – makes decisions about when and how to intervene in ways that bring students closer to the work of scientists.

Small qualitative studies and larger mixed-methods studies have explored student use of SWH in science classrooms. Putti (2011) observed an AP chemistry class of 24 students who used the SWH to improve the investigative experience of students. While some older research showed that students in Advanced Placement chemistry exhibited comparable knowledge to comparable college students, their laboratory skills were more deficient (Zipp, 2002). Putti observed a series of fourteen investigations utilizing no, some, or all of the instructional elements of the SWH. Participating students were then surveyed after four of the investigations about their attitudes toward the SWH sequence, answering a series of questions on a five-point Likert scale. Students agreed or strongly agreed at a rate of 71-88% that completion of the SWH increased their understanding of the chemistry concepts in the unit. When reflecting on individual components of the process, surveys after three of the four labs indicated that one-half to three-fourths of the students found value in the pre-lab discussion focused on identifying the question and defining a data table. Even more students, ranging from 75 – 85%, acknowledged that the pre-lab assignments made them think about the experiments prior to engaging in them and that comparing results among lab groups helped students reach the learning goals.

A mixed methods study by Hand, Wallace, and Yang (2004) explored 93 7^{th} graders' conceptual understanding when using SWH compared to traditional labs. The authors also investigated whether the final product, a traditional lab report (SWH+lab report condition) or a textbook explanation (SWH+textbook explanation condition), added to the effects of SWH on students' conceptual understanding. Post-lab assessments included open-ended conceptual questions as well as a series of multiple-choice questions. On average, students assigned to the SWH+textbook explanation condition scored higher on conceptual questions than students in the SWH+lab report condition. In turn, this latter group scored statistically higher than students in the traditional lab condition. Results favoring the SWH condition persisted on the block of multiple-choice questions with both SWH conditions scoring statistically higher than the traditional condition and not statistically different from each other.

A follow-up investigation focused on the role of the teacher in SWH investigations showed that the teacher's role has a strong influence on student outcomes and especially the equity of those outcomes (Akkus, Gunel, & Hand, 2007). Seven teachers, teaching 592 students in different science disciplines and different grade levels (7-11), divided up their classes to use SWH or traditional lab structures. During the respective interventions, teachers were observed by the research team and assigned an "implementation score" as to their quality of adhering to SWH principles or to traditional lab principles. The observation protocol for SWH illuminates the role that the teacher is expected to play in these settings (Table 1).

Table 1. Observation criteria for high-quality SWH implementation

1. Dialogical interaction

	Patterns of questions asked
	Responses to students' questions
	Reactions to students' answers
2. Focus of learning	
	Sharing of the power relationship
	Types of inquiry investigations
	Public aspects of knowledge (small and whole group discussions)
3. Unit preparation	
	Identifying the big idea
	Tying the big idea to students' prior knowledge
	Use of diversified writing as part of a unit summary

Teachers were rated as 'high-SWH' and 'low-traditional' or 'low-SWH' and 'high-traditional' based on two independent raters. Baseline data indicated no significant differences in science achievement across all classes and conditions. Using pre-test scores for each unit as a covariate, the authors identified a significant effect of 'high-SWH' teaching practice on students' post-test scores as compared to the other three conditions. Further pairwise comparisons indicated that students in 'high-traditional' and 'low-SWH' also out-performed students in the 'low-traditional' classes. Although these results showed that high-quality implementation of SWH benefits students compared to other investigation experiences, even more interesting is the distribution of scores when disaggregating by learning level. In the 'high-SWH' condition, students identified as previously low, middle, or high achieving students in science showed no statistical difference on their post-test scores – the intervention closed the achievement gap among these three levels (a mean difference between high and low students in the 'high-SWH' condition equaled 2.17 points). However, for the other three conditions, the high achieving students significantly out-performed the low achieving students on the final assessment (e.g. in the 'high-traditional' condition, the mean difference between high and low students was 19.63 points). The traditional condition for investigation exacerbated existing achievement levels, creating even greater inequity among students whereas the well-implemented SWH condition resulted in high levels of achievement for all students.

The SWH provides structure for teachers and students when organizing investigations. Teachers, as the community experts, make decisions about the form of student engagement in each aspect of an investigation (e.g. Who will generate the research question?) with the assumption that over time, students can become more responsible for engaging in the scientific practice as an egalitarian community. That is, the experts are providing structure for novice learning to bring them more fully into the community of practice (Lave & Wenger, 1999). Regardless of the form, tools are central parts of communities of practice and can be better established to aid the facilitation of investigations without being reified.

Existing Models of Investigations Embedded within a Community of Practice

Investigations that reflect three-dimensional science learning need not take on a singular form (Schwarz et al., 2017). The creation of a community of practice and its collaborative investigation of the natural world by using a shared repertoire of skills and talk has strong existing models. The following section briefly outlines three different approaches to investigations and the role of the teacher in leading these distinct approaches that all involve a community of practice.

Model-based inquiry. Scientific modeling is the process by which an abstract representation of a phenomena or system of phenomena makes explicit its central features (Harrison & Treagust, 2000). These models can be used for developing causal explanations or making predictions about new phenomena. The development of models is formative because it provides an on-going framework for how students come to understand an idea in contrast to abstract and often meaningless lab activities for which students may find an answer of *what* happens, but never understand *why* it happens (Windschitl et al., 2008). Model-based inquiry provides one framework for teachers to create a community of practice. Although model-based inquiry proceeds iteratively and is based on the needs of the students, the following components are often present (Schwarz et al., 2009):

- The introduction of an anchoring phenomenon
- The creation of an initial model by students
- Empirical testing of the model through investigations
- Evaluation of the model based on evidence from the investigations
- Further testing and revising of the model
- Using the model to predict or explain other phenomena

These modeling elements are not necessarily natural to students and their ability to engage in the process is significantly influenced by the teacher's facilitation (Dass, Head, & Rushton, 2015).

Facilitating model-based inquiry requires the central elements of any community of practice. The teacher's first role is to identify a contextualized, often puzzling, phenomena that anchors ensuing investigations (Windschitl et al., 2008) and brings life to the joint enterprise. The teacher must also establish norms for critique and classroom discourse in which students can share their models and revise models according to new information gained through material activity. Creating this community requires teachers to facilitate on-going discourses and productive talk (Windschitl et al., 2012). Finally, the teacher must provide scaffolds for students to develop a repertoire of skills that pertain to investigations and model development. These scaffolds might prompt students to create before-during-after representations of the phenomenon that can be revised in light of on-going investigations (Windschitl et al., 2008). It may also include guidance in the planning and carrying out of investigations that are pertinent to model formation. Understanding what is needed at a given time in the model-based inquiry cycle, the teacher needs to provide opportunities for investigation of systems that may simulate the phenomenon in question.

Project Based Science (PBS) and Project Based Learning (PBL). PBS and PBL represent similar, but somewhat distinct ways of investigating the natural world. Both PBS and PBL rely on collaborative work among a community that requires self-direction and often draws on multiple disciplines (Mills & Treagust, 2003). The outcome of PBL is focused more on knowledge acquisition as a means for solving a problem. PBS generally includes tasks that are more reflective of authentic practice and generally span longer periods of time than PBL (Mills & Treagust, 2003). PBL has its roots in medical schools and has applications in the K-12 setting (Goodnough & Cashion, 2006), but often does not require extended investigations. In contrast, the literature on PBS shows that extended investigations, conducted in the context of classroom communities, are central features of the pedagogy (Krajcik et al., 2008).

As with other communities of practice, PBS classrooms de-center the role of the teacher, although the teacher's role is still essential to the success of the unit. The first task of the teacher in preparing PBS units begins by identifying a contextualized, relevant phenomenon or central question that draws on students curiosities (Blumenfeld & Krajcik, 2006). Although the teacher may identify a central question that relates to core ideas and standards, room is left for students to engage in the practice of asking scientific questions that contribute to the investigation. The teacher then works with students toward the project's goal by helping students engage in investigations that are aligned with relevant and important science ideas, many of them drawn from students' own questions. To do this, the teacher supports the development of students' planning and carrying out of investigations as described above. As with any format, the role of the teacher in facilitating science talk and productive classroom discussion is also central to learning.

The impact of effectively facilitated PBS classrooms on student outcomes has shown promise. Among other studies, a recent randomized controlled trial in 42 schools in an urban district compared classrooms participating in PBS with classrooms using the district-adopted textbook (Harris et al., 2015). The PBS units provided students multiple opportunities to investigate core science ideas that would help address the overarching question. For two units that were compared, students in the PBS classrooms significantly outscored students in the control condition with effect sizes of .22 and .25.

Citizen Science. Citizen science, and its diverse forms – student-scientist partnerships and participatory action research projects (Krasney & Bonney, 2005) – provide unique investigative experiences that bridge school science and authentic science communities. Scientists needing data from a large geographic range work with K-12 students, teachers, and other citizens to capture evidence for a particular research question. Many projects focus on environmental issues such as water quality monitoring, global climate readings, or the century-old Audubon Christmas Day bird count.

Citizen science projects embedded within middle and high school classrooms have the potential to exist within a community of practice, but it is not guaranteed without the proper structuring by the teacher. With no active involvement from the teacher, citizen science could be limited to students collecting data for others' use (Karrow & Fazio, 2010). To effectively engage students in a community of practice, the teacher must 1) help students comprehend or expand upon the joint enterprise in question; 2) coordinate the community both within the classroom and the broader project community; and 3) help students develop the repertoire for working with large data sets.

First, while the topic and research question are pre-defined by the lead scientist, the teacher must enable students' participation in the joint enterprise. Teachers leading citizen science units must ensure that students understand the posed question and how it fits within a core disciplinary idea or push students to ask their own questions from the data so that they participate in the community as more than data collectors. This process has shown empirical success in both affect and learning outcomes at the undergraduate level. In one case, a faculty member's ecological system was the focal point for dozens of groups of students to collect data, contribute data to a common database, and pose their own unique questions that expanded on the project's central

This paper was commissioned for the committee on Science Investigations and Engineering Design for Grades 6-12. The committee was convened by the Board on Science Education in Washington, DC with support from the Amgen Foundation and the Carnegie Corporation of New York. Opinions and statements included in the paper are solely those of the individual author, and are not necessarily adopted, endorsed, or verified as accurate by the Board on Science Education or the National Academy of Sciences, Engineering, and Medicine.

questions (Brownell et al., 2012; Kloser, Brownell, & Fukami, 2013; Kloser, Brownell, Chiariello, & Fukami, 2011).

Second, teachers must organize the community by identifying the norms for how students will interact with the available data. Will the class work as an entire unit, carving out its own research question or will groups define their own work with the data? Furthermore, the teacher can create opportunities for students to span communities and interact with scientists who lead the overarching project (Price & Lee, 2013). Once questions are posed and data are analyzed, the teacher must then facilitate productive discussion so that students' ideas are central to the learning and that the ideas are making connections to the core disciplinary concepts.

Finally, citizen science data sets can be "messy" in nature in comparison to traditional lab data that is collected in very controlled conditions and variables isolated in ways that drive away empirical noise. This noise, however, can be educative if the teacher helps students develop skills in identifying necessary variables to answer a question, clean the data, and analyze the data using basic statistics.

Research on citizen science has shown mixed results. Students participating in a citizen environmental science project showed improved understanding of environmental research techniques, data interpretation abilities, and the ability to develop inferences (Krasney & Bonney, 2005), but other studies have shown that students' conceptions of research were uninformed in terms of posing scientific questions and that students saw data collection not as a conceptual, but a procedural task (Moss, Abrams, & Kull, 1998). More recent studies have shown positive impacts for both students and teachers. In a student-teacher-scientist partnership project tied to a long-standing program, "Expedition, Yellowstone!", teachers reported significant shifts in their attitudes regarding science and scientists. Furthermore, they were found to significantly shift their pedagogical choices. Students also reported increased positive attitudes toward scientists (Houseal, Abd-El-Khalick, & Destefano, 2014).

Preparing Science Teachers to Engage Students in Investigations

Reshaping middle and high school science investigations from what often follows a linear, cookbook approach to a community of practice faces many obstacles. Professional development (PD) has often been identified as a central means for reforming science education (Hill, 2007), but evidence from the field shows inconsistent results for changes to teachers' practice and improved student outcomes (Yoon, Duncan, Lee, Scarloss, & Shapley, 2007). Reviews of PD research have identified essential components that include active and collaborative teacher engagement, a content focus, work that addresses student learning, longitudinal engagement, and the presence of coherent connections with context and policies (Birman, Desimone, Porter, & Garet, 2000; Borko, Jacobs, & Koellner, 2010; Desimone, 2009). But as Wilson (2013) noted in addressing the "Grand Challenges" of science education, when tested in large-scale experimental settings, the efficacy of the PD elements do not automatically result in changes for teachers or students.

While the field needs to better understand the different elements of PD and how these elements do or do not work together to effect changes to instructional practice, the historical nature of teachers may create barriers for shifting the narrative of science investigations. Lortie's (1975) seminal sociological view into teaching noted that teaching is defined by individualism, presentism, and conservatism. While the strength of these factors can be debated forty years after Lortie's original publication, factors still exist that can foster these traits. School schedules and the lack of common planning time for many teachers can limit collaboration resulting in isolation and individualism. High-stakes testing and accountability measures can occupy teachers' short-term attention that influences the selection of curriculum and instructional approaches toward measures that do not reflect a three-dimensional view of science learning.

Systematic inertia at the district or school level also can create tension for reforms. In a study focused on *NGSS* professional development, teachers noted changes in their own beliefs about effective science teaching after learning about the integration of core ideas, crosscutting concepts, and scientific practices, but their sensemaking was impaired because of competing visions of what quality instruction looked like at their school (Allen & Penuel, 2015). District administrators held tightly to the belief that teachers must front load information such as facts and vocabulary before students could engage in applications or material activity. In order for communities of practice to exist in schools broadly, cultural and political elements may need to change as much as pedagogical components.

Perhaps most influential in diminishing the effects of professional development are teachers' own experiences with linear, individualistic, cookbook investigations that preserve the status quo and resist change. As noted by the National Research Council when discussing teacher professional development needs for STEM integration, "A basic premise of many PD programs reviewed by the committee is that if teachers have not themselves experienced integration [of STEM disciplines], they are not likely to teach integrated curricula…teachers need an understanding of *and experience with* integrated STEM" (Honey, Pearson, Schweingruber, & others, 2014, p. 124). Teachers will more likely reform their practice if they understand how the three dimensions articulated in the *Framework* interact and experience it as learners. The following section describes one framework for thinking about the development of professional practice that could provide teachers conceptual understandings as well as experiential understandings for facilitating a community of practice.

Representing, Decomposing, and Approximating Investigations in Teacher Education

Conceptualizing investigations as labs – activities that have a singular purpose – could result in professional development that conserves the status quo, but conceptualizing scientific investigations as a set of coordinated interactions between the teacher and students, focused on a joint goal, provides a roadmap for professional development. In the former conceptualization, professional development might introduce teachers to specific lab activities that can be reproduced verbatim within their classroom whereas the latter conceptualization suggests that PD would need to be shaped more around the development of professional practice. Grossman et al. (2009) observed the preparation of three relational professions – the clergy, clinical psychology, and teaching – that all share the goal of human improvement. They argue that just as therapists cannot succeed professionally without engaging and working with their clients, teachers must engage and work with their students to aid learning. These three professions also share common ground in the uncertainty under which practice occurs due to the unpredictability of human interaction – especially adolescent human interaction in the classroom. Grossman and her colleagues' investigation of the development of these relational professions identified three key approaches that work in concert to shape practice: representations, decompositions, and approximations. The following sections take up each element of this tripartite framework in light of the affordances and constraints for developing teachers' capacity to facilitate scientific investigations.

Representations of practice take many forms. In education these include videos of classrooms (e.g. Windschitl's https://ambitiousscienceteaching.org/ provides extensive video libraries of entire units of investigation using model-based inquiry), direct observations of teachers, or written cases and transcripts of classroom interactions. As Little (2003) argued, representations of practice allow novices to see the many facets of practice, the interactions, and the tools used. In reshaping the narrative toward investigations as a community of practice, engaging teachers in an authentic community of practice holds possibility as a first-person representation. Research Experiences for Teachers (RETs) embed teachers in college or university research labs during the summer months so as to expose them to cutting edge research, some of which might be translated to classroom curriculum (Enderle et al., 2014). RETs provide opportunities for teachers to not only observe the various roles of scientists and their community of post-docs and graduate students, but also participate peripherally in the lab's interactions as a novice. Participation in an authentic community allows teachers to see representations that are not sanitized, such as those that might occur through selecting only exceptional cases or the best videos of an investigation.

While these opportunities may provide the most realistic representations, the assumption that the observed norms, goals, and interactions can be easily applied to middle and high school classrooms is naïve. Teachers must be given explicit opportunities for reflection about how and why science is conducted in this form and what must be done to replicate the community in their classrooms. Unfortunately, many scientists leading RET programs have little capacity to make this level of reflection effective. As Lakatos (1970) opined, "Most scientists tend to understand little more *about* science than fish about hydrodynamics" (p. 148). As scientists are deeply immersed in their practice, they may be unable to help teachers understand the most important elements of conducting high-quality investigations.

Essentially, representations like RETs often lack the opportunity for decompositions of the practice. Decomposing practice recognizes that teachers are aided by understanding the component parts of practice before they can be integrated into a whole. A three-dimensional view of science education possesses many constituent parts – the curricular planning that brings core disciplinary ideas to the forefront, the scaffolding of question asking and procedure development, or the facilitation of sensemaking discourse to move students toward causal explanations – but teachers embedded within an authentic community of practice or watching in third person may not know the most important parts to which they should attend and reflect. In writing specifically about a three-dimensional approach to science education, Duschl and Bybee (2014) acknowledge the importance of breaking down integrated practice. When discussing professional development for NGSS they recommend "unpacking" a suite of components rather than focusing on them as a set of "fused" components.

Of course, a danger exists in which practice that is normally complex is artificially sectioned into disembodied chunks. For science investigations, the emerging literature on core instructional/high-leverage teaching practices plays a significant role for determining grain-size in working with teachers to decompose the creation of an investigative community of practice. Decompositions might helpfully focus on building a classroom community; scaffolding the design of investigations; and facilitating discussion (Kloser, 2014) in order to have teachers think about investigations as part of a community that socially negotiates norms for data collection and interpretation.

Finally, approximations of practice pull together new understandings from representations and the analysis that occurs during decomposition. To address the needs of three-dimensional science classrooms, approximations – opportunities to try out new skills, moves, or instructional repertoires in a low-stakes environment – likely need to exist outside of traditional opportunities for practice. Existing practica and student teaching may just replicate existing science teaching practices that tend to favor traditional cookbook investigations, if inquiry is present at all. One such opportunity is through targeted summer professional development that allows teachers to work on complex parts of instructional practice in a low-stakes, easily manipulated setting with students, such as a summer camp. Lotter et al. (2016) researched a PD program in which teachers engaged in on-going cycles of practice-teaching and reflection. Surveys and observations at multiple points throughout the year indicated increased self-efficacy in using inquiry teaching methods and changes to instructional practice that reflected inquiry-based teaching methods. The authors cite the importance of the practice component as central to this change.

Rushton and colleagues (2011) researched the impact of a professional development with 23 chemistry teachers in which the teachers took part, as learners, in a series of investigations (representation), engaged in discussions and reflections about the work (decompositions), and had an opportunity to approximate their new understandings in a summer setting with high school students. The authors found that the representations and decompositions shifted teachers' initially naïve views about scientific inquiry toward views that align more with what has now been defined in the *Framework for K-12 Science Education.* However, the opportunity to "try out" elements of their new understandings were seen as essential by teachers to them taking the practice back to their own schools and classrooms. The conceptual shift occurred in the original PD, but teacher needed the opportunity for an approximation. Ultimately, observations of teachers' practice in their school-year classrooms indicated that 75% of the teachers reached the "inquiry threshold" identified by the RTOP observation protocol.

While this paper has tried to be explicit about the differences between notions that have traditionally been considered inquiry and the more three-dimensional community of practice framework, what is salient from the Rushton et al. study is the importance, when possible, for teaching training and professional development to include not only representations, but also approximations. An emerging set of studies on rehearsals – a type of approximation in which the teacher educator or the novice "pauses" the teaching segment to provide feedback or ask a question, respectively, has the potential to attend to the most important roles that a teacher plays in facilitating the many aspects of an investigation in the moment (Davis et al., 2017; Kazemi, Ghousseini, Cunard, & Turrou, 2016; Lampert et al., 2013). Rehearsals narrow the focus on the most important elements of leading a community of practice and recognize that context matters. That is, the rehearsal addresses the needs of the novice teacher as she or he responds to students' (in the case of rehearsals, peer novice teachers) actions during the carrying out of procedures or ideas during sensemaking discussions. Rehearsals with science teachers provide teacher educators contextualized opportunities to address how the teacher uses physical and conceptual tools, how students are engaged in the scientific practice, or how content is represented, thus addressing three-dimensional teaching for novices (Davis et al., 2017).

Growing Together: Teaching Communities for Improving Practice

Acknowledging the important role of representations, decompositions, and approximations for helping teachers reshape their teaching practice will likely result in little change if the necessary support of an ongoing learning community is not present (Coburn et al., 2012). Talbert (2009) notes that little is known about how changes to professional culture occur and that significant professional change is difficult. Heath and Heath's (2010) book, *Switch: How to Change Things When Change is Hard*, identifies several key components of professional change. For one, members of a profession or organization posses a rationale side that can be resistant to change unless it can be envisioned. Bright spots – high-quality representations that point community members to evidence of reformed practice – are necessary to quell rational skepticism. Furthermore, the emotional side of change – its difficulties and risks – must also be addressed. Heath and Heath suggest that "shrinking the change" decreases transformational tension because it allows members of the community to focus on manageable, rather than wholesale change. The National Research Council's *Guide to Implementing the NGSS* (2015a) echoes this approach, advocating that three-dimensional instructional practice will result from curriculum-supported incremental, not wholesale, overnight, change.

Two key tools may help teachers work collaboratively to identify bright spots and incrementally improve their facilitation of investigations: professional learning communities (PLCs) and digital technologies. First, recent research has focused on PLCs as a way to challenge the status quo by "critically examining practice to improve student outcomes" (Seashore, Anderson, and Riedel, 2003, p. 3). Effective PLCs vary in structure but all include shared goals and norms, collaborative opportunities for making public one's practice, and dedicated time to reflective dialogue (Turner et al., 2017). Helping teachers develop the capacity to establish a community of science practice within their classroom requires the long-term engagement of a PLC. Long-term commitments allow participants to incrementally address the difficult, but attainable work of three-dimensional teaching.

For instance, a PLC might focus one entire semester on analyzing artifacts and videos of classroom interactions that help teachers establish community norms for collaborative work and collective understanding. Another PLC might implement a yearlong, highly effective curriculum that presents relevant phenomena to students, allowing teachers to focus on the facilitation of productive, sensemaking talk related to that curriculum. PLC participants can focus on both the teacher's role and the resulting interactions with students by critiquing classroom videos of discussions and analyzing written student samples of work (National Research Council, 2015b). Existing frameworks might also be adopted by PLCs, such as the TAGS framework developed by Tekkumru-Kisa and colleagues (2015). The TAGS framework is composed of two dimensions: 1) the cognitive demand of the science learning task and 2) the level of integration of science content and practices. As an *NGSS*-influenced vision of investigations includes both high cognitive demand and an integration of the three-dimensions outlined in the *Framework*, PLCs could benefit from analyzing tasks associated with investigations before, during, and after they are presented to students.

The *Next Generation Science Standards* introduce a paradigm shift for many science teachers and therefore, facilitation of PLCs will likely require a non-trivial amount of expertise. The literature on PLCs has shown that improvement in practice can result from facilitation within or from an outside expert, but that in cases where the target practice is lacking expertise within the community, then expert facilitation is required (Horn and Kane, 2015). In the case of improving classroom investigations, many science teachers will need an expert to provide evidence of high-quality practice that can be used as a goal for others in the community to reach. Lacking such expertise and bright spot examples, PLC meetings could devolve into "talking shop" about happenings within the school without focusing on practice (Turner et al., 2017, p. 29).

Expert-facilitated PLCs provide opportunities for a community of teachers to see representations of high-quality practice, analyze their own practice, and shrink the change to incrementally focus on learnable elements over time. In addition, PLCs might also benefit from approximations of the practice before facilitating three-dimensional investigations with students (National Research Council, 2015b). These approximations would provide low-stakes opportunities for science teachers to try out elements of practice and gather data about how these enactments. Such approximations might occur in after-school science club settings, summer camps, or even through leading investigations with peer teachers.

Teachers interested in improving investigations within their science classrooms cannot merely collaborate with other teachers. They must collaborate with teachers open to change and committed to a long-term investment of time and effort (Turner et al., 2017). For teachers in rural school settings or in contexts with little commitment to growth, finding this community can be difficult. Contemporary technologies may play a significant role in providing access for all teachers to necessary professional development (National Research Council, 2015b). Three specific digital tools may be of the greatest aid: video conferencing software with screenshare capabilities; video capture and annotation software, and multi-media digital portfolios.

The capacity to use video conferencing software is nearly ubiquitous with current computer cameras. Advancements in the technology now provide pay and free online tools with high-definition resolution, quality audio, and supplementary tools. Most video conferencing programs allow teachers who cannot meet in person to share scanned images of student work, play video, or review digital copies of lesson plans and student tasks. While unique online group norms must be established, video conferencing provides a legitimate PLC experience for isolated science teachers.

Whether in person or through video conferencing, video capture software and multi-media digital portfolios can provide the raw materials for analysis and reflection in PLCs. To improve the nature of investigations, teachers must be willing to make their practice public. Video capture software allows teachers to film their classroom while introducing a phenomenon or eliciting questions for students that are worthy of exploration. Many video capture systems also include annotation systems that allow the teacher, a coach, or the PLC to watch the video ahead of time and raise questions, suggest changes, or highlight effective moves. These tools can streamline PLC meetings so that time can be focused on growth and not on watching the video during the limited synchronous meeting time. Unlike video conferencing tools, however, most current video capture and annotations systems come at a cost ranging from $75 - $150 per teacher per year. Multi-media portfolio tools may provide a more cost effective alternative. Electronic portfolios have been shown to aid teacher growth through the collection of artifacts that reflect teacher practice and student engagement (Stefani, Mason, and Pegler, 2007). More contemporary digital portfolios created as tablet-based applications, expand on the types of artifacts collected from classrooms including images of classroom space, short videos of student and teacher interactions, digital versions of lesson plans, and scanned images of student work and teacher feedback. In combination with PLCs, these digital tools may provide the structure and support necessary to change how investigations are facilitated in middle and high school classrooms.

In summary, the onus of change for how young people engage in investigations in science classrooms should not fall solely on individual teachers. Administrators must not only provide time, curricular, and professional resources for growth, but they also must be exposed to the goals and highly-effective practices envisioned within three-dimensional science classrooms (National Research Council, 2015a). Leveraging contemporary technologies, teachers should have opportunities to enter into their own community of practice. These PLCs will need some level of expert facilitation that can provide strong examples of practice that contrast the status quo. Furthermore, change should take the long view – teachers will grow incrementally and therefore, professional development should focus on one or two core instructional practices for an extended period of time, if possible, supplemented by approximations of these practices in low-stakes contexts.

Conclusion

Engaging students in investigations recognizes that young people are naturally curious about understanding the world around them (National Research Council, 2012). Quality investigations have the potential to address the conceptual, epistemic, and social goals of science education (Duschl, 2008). In light of three-dimensional science learning that guides the *Next Generation Science Standards*, investigations need to be differentiated from single lab activities and viewed as extended opportunities for students to engage in the practices of science while they explore a central disciplinary idea. To do this effectively, teachers must create and facilitate a community of practice (Wenger, 1998) in which teachers and students work together toward a joint goal. While various instructional models exist that can promote this community of practice, all science teachers need to rely on a relatively small set of core instructional practices and tools that can be used to help students develop their repertoire of scientific practices. Emerging empirical evidence supports the role of teachers as facilitators of talk or leaders of model-based inquiry classrooms, but more research is needed that directly addresses the teacher's role in shaping communities of scientific investigations and more must be known about the structure of professional development opportunities that can shift teachers' beliefs and practice.

References

Akkus, R., Gunel, M., & Hand, B. (2007). Comparing an inquiry- based approach known as the Science Writing Heuristic to traditional science teaching practices: Are there differences? *International Journal of Science Education*, *29*(14), 1745–1765.

Allen, C. D., & Penuel, W. R. (2015). Studying teachers' sensemaking to investigate teachers' responses to professional development focused on new standards. *Journal of Teacher Education*, *66*(2), 136–149.

Alozie, N. M., Moje, E. B., & Krajcik, J. S. (2010). An analysis of the supports and constraints for scientific discussion in high school project-based science. *Science Education*, *94*(3), 395–427.

American Association for the Advancement of Science. (1993). *Benchmarks for science literacy*. New York: Oxford University Press.

Andersen, L., & Ward, T. J. (2014). Expectancy-value models for the STEM persistence plans of ninth-grade, high-ability students: A comparison between black, hispanic, and white students. *Science Education*, *98*(2), 216–242.

Ball, D. L., & Forzani, F. M. (2009). The work of teaching and the challenge for teacher education. *Journal of Teacher Education*, *60*(5), 497–511.

Banchi, H., & Bell, R. (2008). The many levels of inquiry. *Science and Children*, *46*(2), 26–29.

Bergman, D., & Morphew, J. (2014). Comparing classroom interactive behaviors of science and non-science pre-service teachers. *The Journal of Classroom Interaction*, *49*(2), 4-10.

Birman, B. F., Desimone, L., Porter, A. C., & Garet, M. S. (2000). Designing professional development that works. *Educational Leadership*, *57*(8), 28–33.

Blumenfeld, P., & Krajcik, J. (2006). Project-based learning. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 333–354). New York: Cambridge University Press.

Borko, H., Jacobs, J., & Koellner, K. (2010). Contemporary approaches to teacher professional development. In E. Baker, B. McGraw, & P. Peterson (Eds.), *International encyclopedia of education* (Vol. 7, pp. 548–556). Oxford, UK: Elsevier.

Brown, B. A., & Kloser, M. (2009). Conceptual continuity and the science of baseball: Using informal science literacy to promote students' science learning. *Cultural Studies of Science Education*, *4*(4), 875–897.

Brownell, S. E., & Kloser, M. J. (2015). Toward a conceptual framework for measuring the effectiveness of course-based undergraduate research experiences in undergraduate biology. *Studies in Higher Education*, *40*(3), 525–544.

Brownell, S. E., Kloser, M. J., Fukami, T., & Shavelson, R. (2012). Undergraduate biology lab courses: comparing the impact of traditionally based "cookbook" and authentic research-based courses on student lab experiences. *Journal of College Science Teaching*, *41*(4), 36–45.

Bybee, R. W. (1997). *Achieving scientific literacy: From purposes to practices.* Portsmouth, NH: Heinemann Educational Books.

Cartier, J. L., Smith, M. S., Stein, M. K., & Ross, D. K. (2013). *5 practices for orchestrating productive task-based discussions in science*. Reston, VA: National Council of Teachers of Mathematics.

Chaiklin, S., & Lave, J. (1996). *Understanding practice: Perspectives on activity and context*. Cambridge, UK: Cambridge University Press.

Chi, M. T. H. (2009). Active-constructive-interactive: A conceptual framework for differentiating learning activities. *Topics in Cognitive Science*, *1*(1), 73–105.

Chin, C. (2007). Teacher questioning in science classrooms: Approaches that stimulate productive thinking. *Journal of Research in Science Teaching*, *44*(6), 815–843.

Coburn, C. E., Russell, J. L., Kaufman, J. H., & Stein, M. K. (2012). Supporting sustainability: Teachers' advice networks and ambitious instructional reform. *American Journal of Education*, *119*(1), 137-182.

Core Practice Consortium. (2017, October 20). Core practice consortium. Retrieved from http://corepracticeconsortium.com/

Crawford, B. (2014). From inquiry to scientific practices in the science classroom. In N. G. Lederman & S. Abell (Eds.), *Handbook of research on science education* (Vol. 2, pp. 515–541). New York, NY: Routledge.

Crawford, B. A. (2000). Embracing the essence of inquiry: New roles for science teachers. *Journal of Research in Science Teaching*, *37*(9), 916–937.

Dass, K., Head, M. L., & Rushton, G. T. (2015). Building an understanding of how model-based inquiry is implemented in the high school chemistry classroom. *Journal of Chemical Education*, *92*(8), 1306–1314.

Davis, E. A., Kloser, M., Wells, A., Windschitl, M., Carlson, J., & Marino, J.-C. (2017). Teaching the practice of leading sense-making discussions in science: Science teacher educators using rehearsals. *Journal of Science Teacher Education*, *28*(3), 275–293.

Desimone, L. M. (2009). Improving impact studies of teachers' professional development: Toward better conceptualizations and measures. *Educational Researcher*, *38*(3), 181–199.

Driver, R., Leach, J. M., Millar, R. R., & Scott, P. (1996). *Young people's images of science*. Buckingham: Open University Press.

Duschl, R. A. (1990). *Restructuring science education: The importance of theories and their development*. New York: Teachers College Press.

Duschl, R. A. (2008). Science education in three-part harmony: Balancing conceptual, epistemic, and social learning goals. *Review of Research in Education*, *32*(1), 268–291.

Duschl, R. A., & Bybee, R. W. (2014). Planning and carrying out investigations: an entry to learning and to teacher professional development around NGSS science and engineering practices. *International Journal of STEM Education*, *1*(1), 12.

Enderle, P., Dentzau, M., Roseler, K., Southerland, S., Granger, E., Hughes, R., … Saka, Y. (2014). Examining the influence of RETs on science teacher beliefs and practice. *Science Education*, *98*(6), 1077–1108.

Finson, K. D. (2002). Drawing a scientist: What we do and do not know after fifty years of drawings. *School Science and Mathematics*, *102*(7), 335–345.

Furtak, E. M., Seidel, T., Iverson, H., & Briggs, D. C. (2012). Experimental and quasi-experimental studies of inquiry-based science teaching: A meta-analysis. *Review of Educational Research*, *82*(3), 300–329.

Gao, S., & Wang, J. (2016). Do variations of science teaching approaches make difference in shaping student content and problem solving achievement across different racial/ethnic groups?. *International Journal of Environmental and Science Education*, *11*(12), 5404–5428.

Germann, P. J., Haskins, S., & Auls, S. (1996). Analysis of nine high school biology laboratory manuals: Promoting scientific inquiry. *Journal of Research in Science Teaching*, *33*(5), 475–499.

Goodnough, K., & Cashion, M. (2006). Exploring Problem-Based Learning in the Context of High School Science: Design and Implementation Issues. *School Science and Mathematics*, *106*(7), 16.

Grossman, P., Compton, C., Igra, D., Ronfeldt, M., Shahan, E., & Williamson, P. (2009). Teaching practice: A cross-professional perspective. *The Teachers College Record*, *111*(9), 2055–2100.

Hand, B., Wallace, C. W., & Yang, E.-M. (2004). Using a Science Writing Heuristic to enhance learning outcomes from laboratory activities in seventh- grade science: quantitative and qualitative aspects. *International Journal of Science Education*, *26*(2), 131–149.

Harris, C. J., Penuel, W. R., D'Angelo, C. M., DeBarger, A. H., Gallagher, L. P., Kennedy, C. A., … Krajcik, J. S. (2015). Impact of project-based curriculum materials on student learning in science: Results of a randomized controlled trial. *Journal of Research in Science Teaching*, *52*(10), 1362–1385.

Harrison, A. G., & Treagust, D. F. (2000). A typology of school science models. *International Journal of Science Education*, *22*(9), 1011–1026.

Heath, C. & Heath, D. (2010). *Switch: How to change things when change is hard.* New York: Broadway.

Hill, H. C. (2007). Learning in the teaching workforce. *The Future of Children*, *17*(1), 111–127.

Honey, M., Pearson, G., Schweingruber, H., & others. (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research*. Washington DC: National Academies Press.

Horn, I. & Kane, B. (2015). Opportunities for professional learning in mathematics teacher workgroup conversations: Relationships to instructional expertise. *Journal of the Learning Sciences, 24*, 373-418.

Houseal, A. K., Abd-El-Khalick, F., & Destefano, L. (2014). Impact of a student–teacher–scientist partnership on students' and teachers' content knowledge, attitudes toward science, and pedagogical practices. *Journal of Research in Science Teaching*, *51*(1), 84–115.

Karrow, D., & Fazio, X. (2010). Educating-within-place: Care, citizen science, and ecojustice, SpringerLink. *Cultural Studies and Environmentalism*, *3*, 193–214.

Kazemi, E., Ghousseini, H., Cunard, A., & Turrou, A. C. (2016). Getting inside rehearsals: Insights from teacher educators to support work on complex practice. *Journal of Teacher Education*, *67*(1), 18–31.

Kloser, M. (2014). Identifying a core set of science teaching practices: A delphi expert panel approach. *Journal of Research in Science Teaching*, *51*(9), 1185–1217.

Kloser, M., Brownell, S. E., Chiariello, N. R., & Fukami, T. (2011). Integrating teaching and research in undergraduate biology laboratory education. *PLoS Biology*, *9*(11), e1001174.

Kloser, M., Brownell, S., & Fukami, T. (2013). Effects of a research-based ecology lab course: A study of nonvolunteer achievement, self-confidence, and perception of lab course purpose. *Journal of College Science Teaching*, *42*(2), 90–99.

Kloser, M., Wilsey, M., Madkins, T., & Windschitl, M. (In press). Connecting the dots: Secondary science teacher candidates' uptake of the core practice of facilitating sensemaking discussions from teacher education experiences. *Teaching and Teacher Education*.

Krajcik, J., McNeill, K. L., & Reiser, B. J. (2008). Learning-goals-driven design model: Developing curriculum materials that align with national standards and incorporate project-based pedagogy. *Science Education*, *92*(1), 1–32.

Krajcik, J. S. (2015). Three-dimensional instruction: Using a new type of teaching in the science classroom. *Science and Children*, *53*(3), 6–8.

Krajcik, J. S., & Czerniak, C. M. (2014). *Teaching science in elementary and middle school: A project-based approach*. London: Routledge.

Krasney, M. E., & Bonney, R. (2005). Environmental Education and Advocacy: Changing Perspectives of Ecology and Education. In E. A. Johnson & M. J. Mappin (Eds.), *Environmental Education and Advocacy* (pp. 292–316). Cambridge: Cambridge University Press.

Kuhn, T. S. (1962). *The structure of scientific revolutions*. Chicago: University of Chicago Press.

Lakatos, I. (1970). Falsification and the methodology of scientific research programmes. In I. Lakatos & A. Musgrave (Eds.), *Criticism and the growth of knowledge* (pp. 91–196). Cambridge: Cambridge University Press.

Lampert, M., Franke, M. L., Kazemi, E., Ghousseini, H., Turrou, A. C., Beasley, H., … Crowe, K. (2013). Keeping it complex: Using rehearsals to support novice teacher learning of ambitious teaching. *Journal of Teacher Education*, *64*(3), 226–243.

Latour, B., & Woolgar, S. (1986). *Laboratory life: The construction of scientific facts*. Princeton, NJ: Princeton University Press.

Lave, J., & Wenger, E. (1999). *Situated learning: Legitimate peripheral participation*. Cambridge, UK: Cambridge University Press.

Lemke, J. L. (1990). *Talking science: Language, learning, and values* (Vol. 1). Norwood, NJ: Ablex Publishing Corporation.

Little, J. W. (2003). Inside teacher community: Representations of classroom practice, *105*, 913–945.

Longino, H. E. (1990). *Science as social knowledge*. Princeton, N.J.: Princeton University Press Princeton, NJ.

Lortie, D. C. (1975). *Schoolteacher: A sociological study*. Chicago: University of Chicago Press.

Lotter, C., Smiley, W., Thompson, S., & Dickenson, T. (2016). The impact of a professional development model on middle school science teachers' efficacy and implementation of inquiry. *International Journal of Science Education*, *38*(18), 2712–2741.

Magnusson, S. J., Palincsar, A. S., & Templin, M. (2004). Community, culture, and conversation in inquiry based science instruction. In L. B. Flick & N. Lederman (Eds.), *Scientific inquiry and nature of science* (pp. 131–155). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Marshall, J. C., & Alston, D. M. (2014). Effective, sustained inquiry-based instruction promotes higher science proficiency among all groups: A 5-year analysis. *Journal of Science Teacher Education*, *25*(7), 807–821.

Marshall, J. C., Smart, J., Lotter, C., & Sirbu, C. (2011). Comparative analysis of two inquiry observational protocols: Striving to better understand the quality of teacher-facilitated inquiry-based instruction. *School Science and Mathematics*, *111*(6), 306–315.

McNeill, K. L., & Pimentel, D. S. (2010). Scientific discourse in three urban classrooms: The role of the teacher in engaging high school students in argumentation. *Science Education*, *94*(2), 203–229.

Michaels, S., & O'Connor, C. (2017). From recitation to reasoning: Supporting scientific and engineering practices through talk. In C. V. Schwarz, C. Passmore, & B. J. Reiser (Eds.), *Helping students make sense of the world using next generation science and engineering practices* (pp. 311–336). Arlington, VA: NSTA Press.

Mills, J. E., & Treagust, D. F. (2003). Engineering education - is problem-based or project-based learning the answer? *Australian Journal of Engineering Education*, 2–16.

Moll, L. C., Amanti, C., Neff, D., & Gonzalez, N. (1992). Funds of knowledge for teaching: Using a qualitative approach to connect homes and classrooms. *Theory into Practice*, *31*(2), 132–141.

Moss, D. M., Abrams, E. D., & Kull, J. A. (1998). Can we be scientists too?: Secondary students' perceptions of scientific research from a project-based classroom. *Journal of Science Education and Technology*, *7*(2), 149–161.

National Research Council. (1996). *National science education standards*. Washington, DC: National Academies Press.

National Research Council. (2005). *America's lab report: Investigations in high school science*. Washington, DC: National Academies Press.

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: The National Academies Press.

National Research Council. (2015a). *Guide to implementing the Next Generation Science Standards*. Washington, DC: The National Academies Press.

National Research Council. (2015b). *Science teachers' learning: Enhancing opportunities, creating supportive contexts*. Washington, DC: The National Academies Press.

NGSS Lead States. (2013). *Next Generation Science Standards: For states, by states*. Washington DC: The National Academies Press.

Planck, M. (1949). *Scientific autobiography and other papers*. New York: Philosophical Library.

Price, C. A., & Lee, H.-S. (2013). Changes in participants' scientific attitudes and epistemological beliefs during an astronomical citizen science project. *Journal of Research in Science Teaching*, *50*(7), 773–801.

Putti, A. (2011). High school students' attitudes and beliefs on using the science writing heuristic in an advanced placement chemistry class. *Journal of Chemical Education*, *88*(4), 516–521.

Reckwitz, A. (2002). Toward a theory of social practices: A development in culturalist theorizing. *European Journal of Social Theory*, *5*(2), 243–263.

Rushton, G. T., Lotter, C., & Singer, J. (2011). Chemistry teachers' emerging expertise in inquiry teaching: the effect of a professional development model on beliefs and practice. *Journal of Science Teacher Education*, *22*(1), 23–52.

Schroeder, C. M., Scott, T. P., Tolson, H., Huang, T.-Y., & Lee, Y.-H. (2007). A meta-analysis of national research: Effects of teaching strategies on student achievement in science in the United States. *Journal of Research in Science Teaching*, *44*(10), 1436–1460.

Schwab, J. J. (1962). The teaching of science as inquiry. In J. Schwab & P. Brandwein (Eds.), *The teaching of science* (pp. 1–104). Cambridge, MA: Harvard University Press.

Schwarz, C. V., Passmore, C., & Reiser, B. J. (2017). Moving beyond "knowing about" science to making sense of the world. In C. V. Schwarz, C. Passmore, & B. J. Reiser (Eds.), *Helping students make sense of the world using next generation science and engineering practices* (pp. 3–21). Arlington, VA: NSTA Press.

Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Achér, A., Fortus, D., … Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching*, *46*(6), 632–654.

Seashore, K., Anderson, A., & Reidel, E. (2003, January). *Implementing arts for academic achievement: The impact of mental models, professional community, and interdisciplinary teaming.* Paper presented at the seventeenth conference of the International Congress for School Effectiveness and Improvement, Rotterdam.

Stefani, L., Mason, R., & Pegler, C. (2007). *The educational potential of e-portfolios: Supporting personal development and reflective learning*. New York: Routledge.

Taber, K. S. (2010). Constructivism and direct instruction as competing instructional paradigms: An essay review of Tobias and Duffy's constructivist instruction: Success or failure? *Education Review*, *13*(8), 1–44.

Talbert, J. E. (2009). Professional learning communities at the crossroads: How systems hinder or engender change. In A. Hargreaves et al. (Eds.), *Second international Handbook of Educational Change* (pp. 555-571), Dordrecht, Netherlands: Springer.

Tekkmumru-Kisa, M., Stein, M. K., Schunn, C. (2015). A framework for analyzing cognitive demand and content-practices integration: Task analysis guide in science. *Journal of Research in Science Teaching*, *52*(5), 659-685.

Thompson, J., Windschitl, M., & Braaten, M. (2013). Developing a theory of ambitious early-career teacher practice. *American Educational Research Journal*, *50*(3), 574–615.

Tolbert, S., Stoddart, T., Lyon, E. G., & Solãs, J. (2014). The next generation science standards, common core state standards, and English learners: Using the SSTELA framework to prepare secondary science teachers. *Issues in Teacher Education*, *23*(1), 65.

Turner, J. C., Christensen, A., Kackar-Cam, H. Z., Fulmer, S. M., & Trucano, M. (2017). The development of professional learning communities and their teacher leaders: An activity systems analysis. *Journal of the Learning Sciences*. Retrieved from http://www.tandfonline.com/doi/full/10.1080/10508406.2017.1381962.

Van Gog, T., Ericsson, K. A., Rikers, R. M., & Paas, F. (2005). Instructional design for advanced learners: Establishing connections between the theoretical frameworks of cognitive load and deliberate practice. *Educational Technology Research and Development*, *53*(3), 73–81.

Vygotsky, L. (1978). *Mind in society: The development of higher psychological processes*. Cambridge, MA: Harvard University Press.

Weiss, I. R., Pasley, J. D., Smith, P. S., Banilower, E. R., & Heck, D. J. (2003). *Looking inside the classroom: A study of K-12 mathematics and science education in the United States*. Chapel Hill, NC: Horizon Research Inc.

Wenger, E. (1998). *Communities of practice: Learning, meaning, and identity*. Cambridge, UK: Cambridge University Press.

Wilsey, M., & Kloser, M. (2015). No blue ribbon: Reforming science fairs in middle and high school science education. *The Science Teacher, 82*(8), 53–59.

Wilson, C. D., Taylor, J. A., Kowalski, S. M., & Carlson, J. (2009). The relative effects of inquiry-based and commonplace science teaching on students' knowledge, reasoning, and argumentation about sleep concepts: A randomized control trial. Presented at the Society for Research on Educational Effectiveness, Evanston, IL.

Wilson, S. M. (2013). Professional development for science teachers. *Science*, *340*(6130), 310–313.

Windschitl, M. (2017). Planning and carrying out investigations. In C. V. Schwarz, C. Passmore, & B. J. Reiser (Eds.), *Helping students make sense of the world using next generation science and engineering practices* (pp. 135–157). Alexandria, VA: NSTA Press.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, *92*(5), 941–967.

Windschitl, M., Thompson, J., Braaten, M., & Stroupe, D. (2012). Proposing a core set of instructional practices and tools for teachers of science. *Science Education*, *96*(5), 878–903.

Yoon, K. S., Duncan, T., Lee, S. W. Y., Scarloss, B., & Shapley, K. (2007). *Reviewing the evidence on how teacher professional development affects student achievement* (Issues and Answers

Report No. REL 2007 No. 033). Washington, DC: U.S. Department of Education, Regional Educational Laboratory Southwest.

Zipp, A. P. (2002). Retrieved from http://apcentral.collegeboard.com/apc/members/courses/teachers_corner/155053.html?type=print