A Geometric Model to Teach Nature of Science, Science Practices, and Metacognition

By Matthew Nyman and Tyler St. Clair

Using the science practice model in science classes for preservice teachers addresses three important aspects of science teacher preparation: teaching the nonlinear nature of scientific process, using scientific practices rather than the ambiguous term inquiry-based*, and emphasizing the process of metacognition as an important tool in teaching and learning. The science practice model is built on two other models for scientific practice: Harwood's (2004) activity model for inquiry and the eight science practices used in the* Next Generation Science Standards *(NGSS Lead States, 2013). In this article we provide two examples of how we used the model in our work with preservice teachers.*

The linear scientific method has been a science teaching staple for decades, but recently it has taken a pedagogical and philosophical beating because of several factors (National Research Council, 2012; *Understanding Science*, an online resource developed by the University of California Museum of Paleontology at UC Berkeley available at www.understandingscience.org). To be clear, there is some usefulness to the linear scientific method, especially as a tool for organizing and reporting results. The linear model also provides a framework for developing and testing questions by controlled experiment (*Understanding Science* website). However, as a model for representing authentic scientific practice, it is both simplistic and inaccurate (National Research Council, 1996). Some criticisms of the scientific method include that the model neglects the social and cultural aspects of science; diminishes the importance of creativity and serendipity in scientific work; suggests that there is one set procedure for scientific investigations; and provides the false impression that scientific work somehow comes to a final, correct answer, rather than a theory or model-building exercise that provides the most probable explanation of the data (Lederman, Abd El Khalick, Bell, & Schwartz, 2002).

Science educators have also struggled with developing a coherent and concise framework that describes the work of scientists that can guide student learning. In secondary education there have been several efforts to systemize science education through standards-based approaches with a fundamental goal of providing a framework for science teaching and learning, including how science is done. Standard-based frameworks have also informed college and university science and science methods classes for preservice teachers. Both the *National Science Education Standards* (National Research Council, 1996) and the *Benchmarks for Science Literacy* (American Association for the Advancement of Science, 1993) used the term *scientific inquiry* as the model for how science is done and should be taught. The *inquiry-based* approach resulted in a plethora of inquiry-based science teacher preparation and professional development efforts and development of inquiry-based curricula that sought to promote more experiential learning rather than traditional pedagogy that involved listening, memorizing, and reading a textbook.

However, science teacher educators, K–12 teachers, and university science faculty differed on the exact definition of *inquiry* resulting in confusion about the actual science practices that constituted scientific inquiry (National Research Council, 2012). The *Next Generation Science Standards* (*NGSS*; NGSS Lead States, 2013) attempt to address this issue by outlining eight specific science practices that scientists engage in while doing their work. In this article, we present a tool that we have used in our science classes for preservice teachers that is modeled on the eight *NGSS* science practices and can be used to clarify the nonlinear nature of scientific work and emphasize aspects of science (like the collaborative nature of science) that are absent from linear models. The science practice model is built on two pieces of previous work: (a) the work of William Harwood (2004), who developed the activity model for inquiry, and (b) the eight *NGSS* science practices. Our model combines Harwood's geometrical model with the eight *NGSS* science practices into a tool that can readily be used in either science content or methods classes for preservice teachers.

Other models for scientific process

The linear scientific method is portrayed as a list of specific and ordered activities (Figure 1). It is doubtful that any intellectual inquiry or investigation proceeds by this simple process. Some models include arrows to show that the process may be repeated; however, the model still lacks important intellectual, social, and procedural activities (Figure 2).

Harwood (2004) published a new model for inquiry, referred to as the activity model for inquiry, which represents the process of science inquiry as a series of 10 scientific activities in which scientists engage. Harwood (2004) identified these activities on the basis of interviews with scientists from different disciplines and tested his model by observing a university-level, inquiry-based biology lesson. Harwood (2004) observed that students' work activities did not follow a set linear path as prescribed by the linear scientific method, but rather was random, and revisited some tasks more than once during the lab. As a visual metaphor Harwood developed a nonagon (nine-sided figure) where each science activity occupies the vertices and developing scientific question lies on the inside of the diagram (Figure 3).

The *NGSS* (NGSS Lead States, 2013) and *A Framework for K–12 Science Education* (National Research Council, 2012), on which the standards were developed, present science as a set of eight science practices. As stated in the *Framework*, the term *practices* was used (instead

FIGURE 1

Linear model of the scientific method.

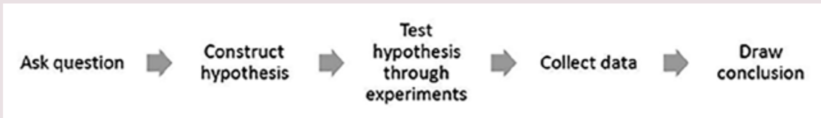


FIGURE 2

Modified linear model of the scientific method.

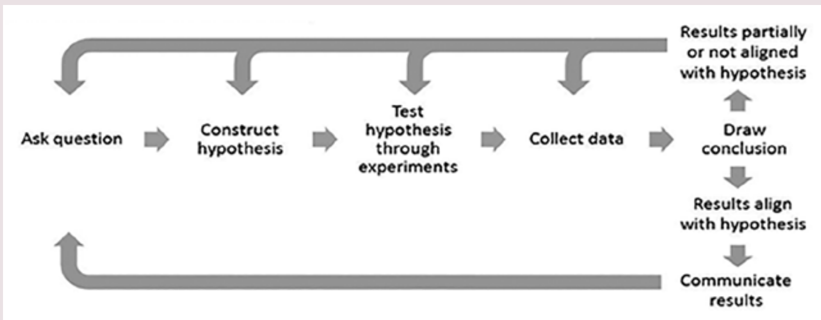


FIGURE 3

Harwood (2004) activity model for inquiry.

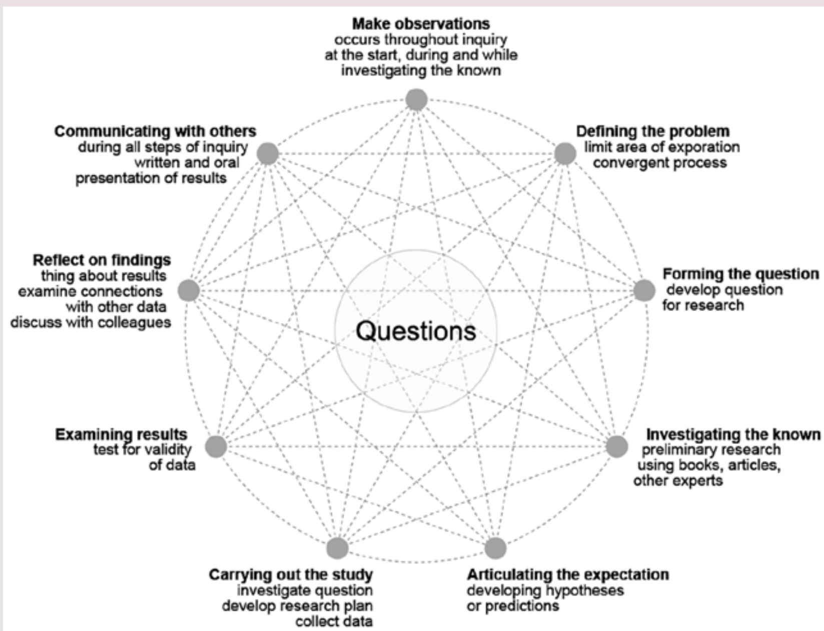
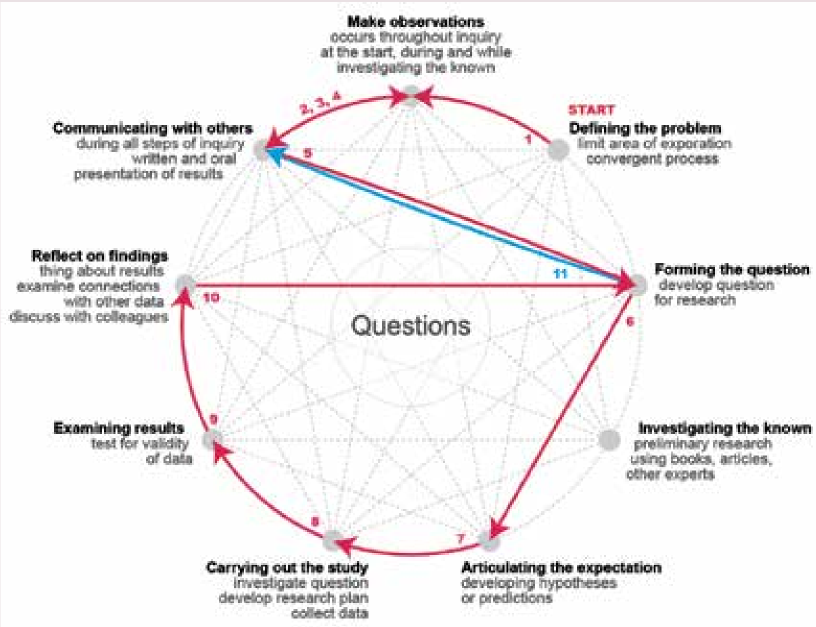


FIGURE 4

Harwood (2004) activity model for inquiry annotated for candle-burning inquiry. The colored arrows in each of the models indicate that the science practice was used more than once.



of *skills*) to emphasize that scientific inquiry "requires coordination of both knowledge and skills simultaneously." This stance circumvents the instructional controversy around whether to emphasize science content or process in science instruction. Using the *Framework* of science practices also provides a means for teachers to help students participate in deliberate and specific practices rather than relying on the nebulous term of *inquiry*, which has resisted clear definition. The *Framework* states that a focus on practices will provide students an opportunity to develop scientific habits of mind; to engage in practices that have previously been underemphasized in K–12 science classrooms, such as modeling and arguing from evidence; to gain an appreciation and understanding of how scientific knowledge is developed; and to see that there are numerous paths to scientific knowledge (not just through controlled experiments).

The *NGSS* science practice model

We wanted to develop a model for our work with preservice teachers that helps to teach scientific practices, exemplifies the nonlinear nature of scientific work, and helps to develop students' metacognition related to understanding science. One of us has previously used Harwood's (2004) activity model for inquiry in science teaching as a tool to accomplish these goals (Figure 4). The general procedure was to have students track the specific science practices on a paper copy of Harwood's activity model for inquiry while they were completing an inquiry-based experiment or project. For example, as an introduction to inquiry and the nature of science, preservice elementary education majors students were required to develop an open inquiry (Banchi & Bell, 2008) investigation related to a candle burning (Wise & Bluhm, 2008). The first step to the inquiry lab was to define the problem, that is, limit the area for exploration. The problem for the students was to develop an investigation around a candle burning. On a paper copy of the activity model for inquiry, students would mark "defining the problem" with the number 1 and briefly describe what they did during this step (not included on diagram). Next, students were given a single candle and instructed to make 20 observations of the candle without using the words *candle* and *wick* in their descriptions. This step was recorded on the model by drawing an arrow from "defining the problem" to "make observations," where the number 2 was written. Observations were then collected from the class, organized in a word cloud, and shared with the rest of the class. This was an activity of communicating with others, so the number 3 was placed on that location, a short description of the activity was written, and a line was drawn between "make observations" and "communicating with others." A second round of observations and communication was completed resulting in two more arrows between "communicating with others" and "make observations." This was continued throughout the lab. Note that students did not develop a research question until Step 6. This tracking process is similar to the one described on the *Understanding Science* website (www.understandingscience.org), where steps from science case studies (e.g., extinction of the dinosaurs) are tracked on the *Understanding Science* model.

We used Harwood's activity model for inquiry in physical science courses for preservice elementary teachers, professional development for K–12 science teachers, university geology labs for both majors and nonmajors, and field-based courses for teachers. The model with arrows and numbers (Figure 4) clearly illustrates and emphasizes the nonlinear nature of scientific work. Students also recognized that some steps are not completed in all investigations. For example, for the candle burning inquiry, the step “investigating the known” was not completed. We have also found that the process of stopping, evaluating the science practice that is currently being used, and mapping out the sequence of activities provides students time to evaluate what exactly they are doing in the lab and to think about their learning and doing process, that is, to use metacognition in their work.

The next step in developing the *NGSS* science practice model involved modifying the imagery developed by Harwood (2004) to fit the eight *NGSS* science practices (Figure 5). Unlike Harwood’s model, we chose not to put one of the major activities at the center of the diagram, which we left open to more easily draw in the procedural paths. In the next section, we provide two examples of where we used this model in our work with preservice teachers.

NGSS science practice model

Example 1: Elementary preservice teachers

The first example of the use of the *NGSS* science practice model is from a course for preservice elementary teachers that focused on scientific inquiry and served as a bridge class between science content courses and science methods courses. We used the *NGSS* science practice model during three different laboratories; we will report on results from a guided inquiry owl pellet dissection lab.

Figure 6 shows the results of a student tracking the group’s activities using the *NGSS* science practice model. Table 1 shows a short description from one group of the specific tasks they were undertaking. Clearly, the crossing lines and returning to the same science practices more than once demonstrates the nonlinear process for the owl pellet dissection. Some student groups excluded some of the steps—for example, engaging in argument from evidence. This reflection on their own practice as it was happening helped students see

FIGURE 5

Science practice model.

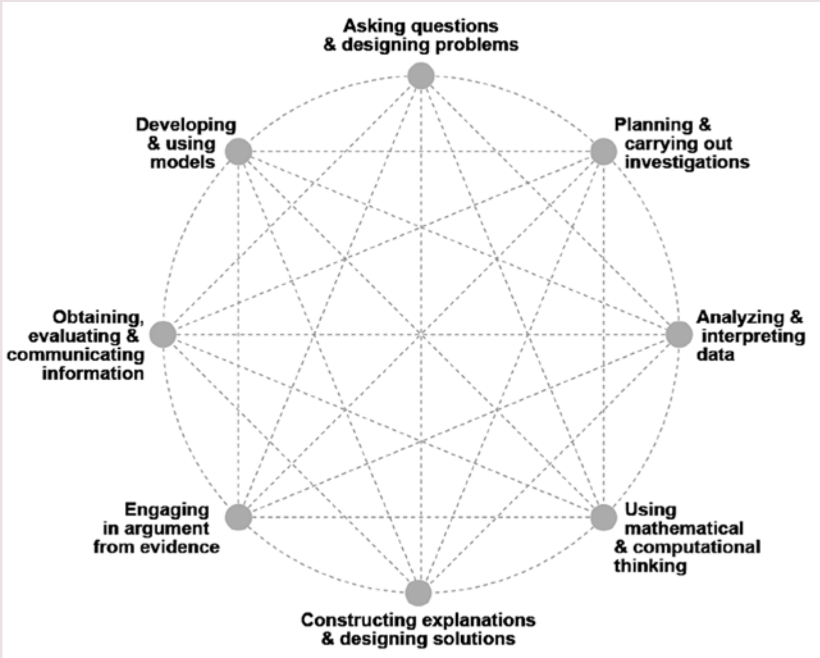


FIGURE 6

Science practice model annotated for owl pellet inquiry.

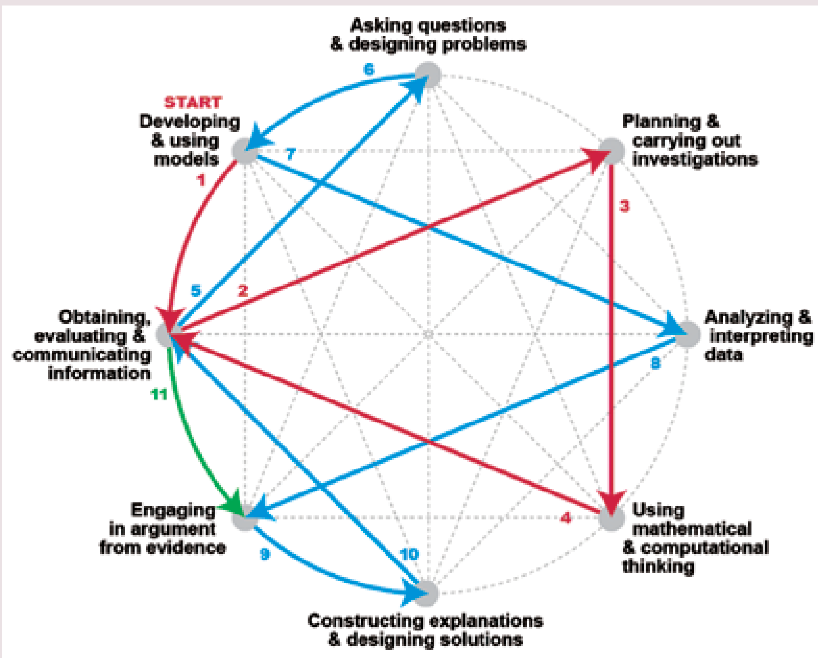


TABLE 1

Steps for the *NGSS* practice model referred to in Figure 6.

Steps	Specifics of practice
1	Made a food web model.
2	We got our owl pellets and he gave us questions.
3	We then planned out how we were going to make all the measurements and then carried it out.
4	Used mathematical thinking to make measurements.
5	Dissected the owl pellet, found bones, and other information.
6	Asked the question, "What bones are these?"
7	We used an owl pellet bone chart model to answer the above question.
8	We then used the data and the owl pellet bone model to interpret and understand what creature the bones belonged to.
9	We are debating over the different possibilities of what the bones could be and why they would be the bones for that animal.
10	We believe we know what the animal bones we found and constructed an explanation.
11	As an even larger group (the whole class) we talked about what we found, communicating new information. We all obtained new information.
12	We then engaged in argument to create a new food web and what the different bones are.

that not all aspects of scientific practices are used in every science activity and further helped to dispel the myth of the singular scientific method as suggested by linear models.

The reflection on science practices was perceived to be very helpful by the students, and they reported during the end-of-term class discussion that using the *NGSS* science practice model was the aspect of the class students liked and learned from the most. In particular, students reported that this technique was good practice in understanding the process of science, helping them to think about how science was really done, to define and provide real examples of the different science practices (because they were doing them), and to think about what they were doing during their work (metacognition).

Example 2: Middle and high school preservice teachers

We also used the *NGSS* science practice model in a similar course for middle and high school preservice teachers. We applied the procedure to an exercise on plate tectonics called discovering plate boundaries (Sawyer, Henning, Ship, & Dunbar, 2005) that was used to illustrate the importance of patterns (an *NGSS* crosscutting concept) and as a platform for conducting a model-based inquiry. During this jigsaw activity, students made observations of the global distribution of four types of data (volcano locations, earthquake depth and epicenter, topography and age of the ocean floor) and then developed a classification scheme for each data type. Students then developed a new classification model incorporating all the data types, which they compared with the commonly accepted plate tectonic model for a specific plate. As described earlier, students were required to track their specific activities as they worked through the project. Figure 7 shows an example of a student's work.

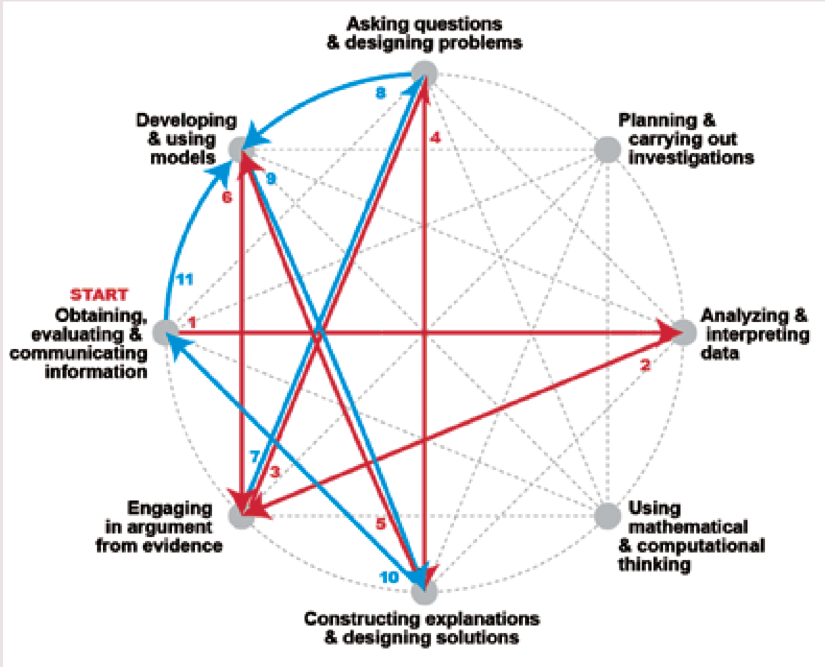
We unpacked the use of the *NGSS* science practice model in a class discussion following completion of the activity. As with the other course, students found the activity to be useful. These students were not so "surprised" by the illustration of the nonlinear nature of science provided by the exercise. This is probably because, prior to the discovering plate boundary project, students reviewed and made presentations of case studies on scientific discoveries from the *Understanding Science* website (www.understandingscience.org). The case studies clearly illustrate the nonlinear nature of the different science discoveries. A second possibility is that most of the students in the course are science majors, and during the class we learned that many had conducted scientific research as independent projects or summer internships.

Theoretical considerations for science practice model

The *Framework* and the *NGSS* were informed by research in how students learn as summarized in numerous publications (e.g., Bransford, Brown, & Cocking, 2000; Corcoran, Mosher, & Rogat, 2009; Duschl, Schweingruber, & Shouse, 2007). Foundational cognitive science ideas that inform these documents include the importance of students actively constructing scientific knowledge across grade bands; the application of metacognition whereby students closely question and examine their own learning; and the use of fundamental frameworks and/or theories for organizing knowledge and skills for later retrieval, transfer, and application. Our work with the science practice model supports a constructivist view of learning where preservice teachers, who have in general been "raised" on the linear model for science, engage in scientific inquiry processes while monitoring their progress through using different science practices. The practice of documenting each step in the inquiry on the science practice model challenges cognitive structures that are rooted by previous experiences and provides an avenue for preservice teachers to discover the nonlinear nature of scientific inquiry. We encourage preservice teachers' metacognition by requiring each group to write down the activities that they engaged in for each science practice (Table 1). Our mode of teaching supports the opportunity for knowledge construction; we provided a discovery learning experience rather than more direct instruction on the nature of science. Finally, the constructivist framework explains the "lack of surprise" or more limited learning for the middle and high school preservice teachers. Many of these preservice teachers had either constructed this knowledge from the prior classroom learning experience using the *Understanding Science* website and/or from their own experience doing scientific research.

FIGURE 7

Science practice model annotated for discovering plate boundary inquiry.



Application across grade bands

Our work focused on using the science practice model with preservice teachers and not in K–12 classrooms. However, one of us (Nyman) has worked with in-service teachers who have used Harwood's (2004) model with their students, although there has been no follow-up study to investigate impacts on teaching practice and student learning. The *NGSS* clearly scaffold the science practices for grade bands; for example, the K–2 asking questions practice indicates that students should ask questions on the basis of observations, whereas in the 3–5 grade band, expectations are that students will identify variables and identify scientific versus nonscientific questions, a much more cognitively challenging effort. Because *NGSS* science practices are scaffolded by grade band, we believe the science practice model can be used with all grades and encourage classroom teachers to use a similar procedure as outlined in this article. Skillful and guided application of the science practice model would probably be required for the K–2 and 3–5 grade bands because of the large number of practices and complex geometry of the model.

Closing remarks

To effectively teach science using an investigative approach (i.e., an inquiry-based approach), preservice teachers need inquiry-based learning and opportunities that provide models for their future instruction. It also serves preservice teachers for instructors to couple investigative learning opportunities with instruction on the nature of science—for example, the nonlinearity of science processes and the fact that not all science investigations follow the same procedural steps. With the growing acceptance of the *NGSS*, coupling these learning opportunities with science practices provides an important link between the training of preservice teachers and their future practice.

Both Harwood's (2004) activity model and the *NGSS* science practices provide a means to specifically identify the different practices in which scientists engage while conducting investigations, therefore avoiding the ambiguity engendered by use of the term *inquiry based*. In this article, we have shown that the science practice model, which combines the *NGSS* science practices into a similar visual model as Harwood's activity model, provides a means to successfully teach preservice teachers about the nature of science while integrating the eight science practices of the *NGSS*. Furthermore, the science practice model provides a tool for preservice teachers to more deeply reflect on what it means to do science. ■

References

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

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

Bransford, J., Brown, A. L., & Cocking, R. R. (2000). *How people learn: Brain, mind, experience, and school* (Expanded ed.). Washington, DC: National Research Council.

Corcoran, T., Mosher, F. A., & Rogat, A. (2009). *Learning progressions in science: An evidence-based approach to reform* (CPRE Research Report# RR-63). Philadelphia, PA: Consortium for Policy Research in Education.

Duschl, R. A., Schweingruber, H. A., & Shouse, A. W. (2007). Taking science to school. *Learning and teaching science in grades K–8*. Washington, DC: National Academies Press.

Harwood, W. S. (2004). A new model for inquiry: Is the scientific method dead? *Journal of College Science Teaching*, *33*(7), 29–33.

Lederman, N. G., Abd El Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching*, *39*, 497–521.

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

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

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. Washington, DC: National Research Council.

Sawyer, D. S., Henning, A. T., Ship, S., & Dunbar, R. W. (2005). A data rich exercise for discovering plate boundary processes. *Journal of Geoscience Education*, *53*, 65–74.

Wise, K., & Bluhm, W. J. (2008). Scientific observation and the learning cycle: Burning the candle at both ends. *Journal of College Science Teaching*, 37(3), 68–60.

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