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A Science Education that Promotes the Characteristics of Science and Scientists: Features of Teaching

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Editor note: This is the third in a series of four articles regarding the nature of science, and how it relates to STEM education.

Effectively teaching about science, technology, engineering and mathematics (STEM) is far more complex than policymakers, the public, and even many teachers realize. Leinhardt and Greeno (1986, p. 75) write that "teaching occurs in a relatively ill-structured, dynamic environment", and this is even more so the case when attempting to teach STEM through inquiry (activities that require significant student decision-making and sense-making, and the necessary pedagogical practices that support student learning in those experiences) and as inquiry (helping students understand how knowledge in STEM disciplines is developed and comes to be accepted).

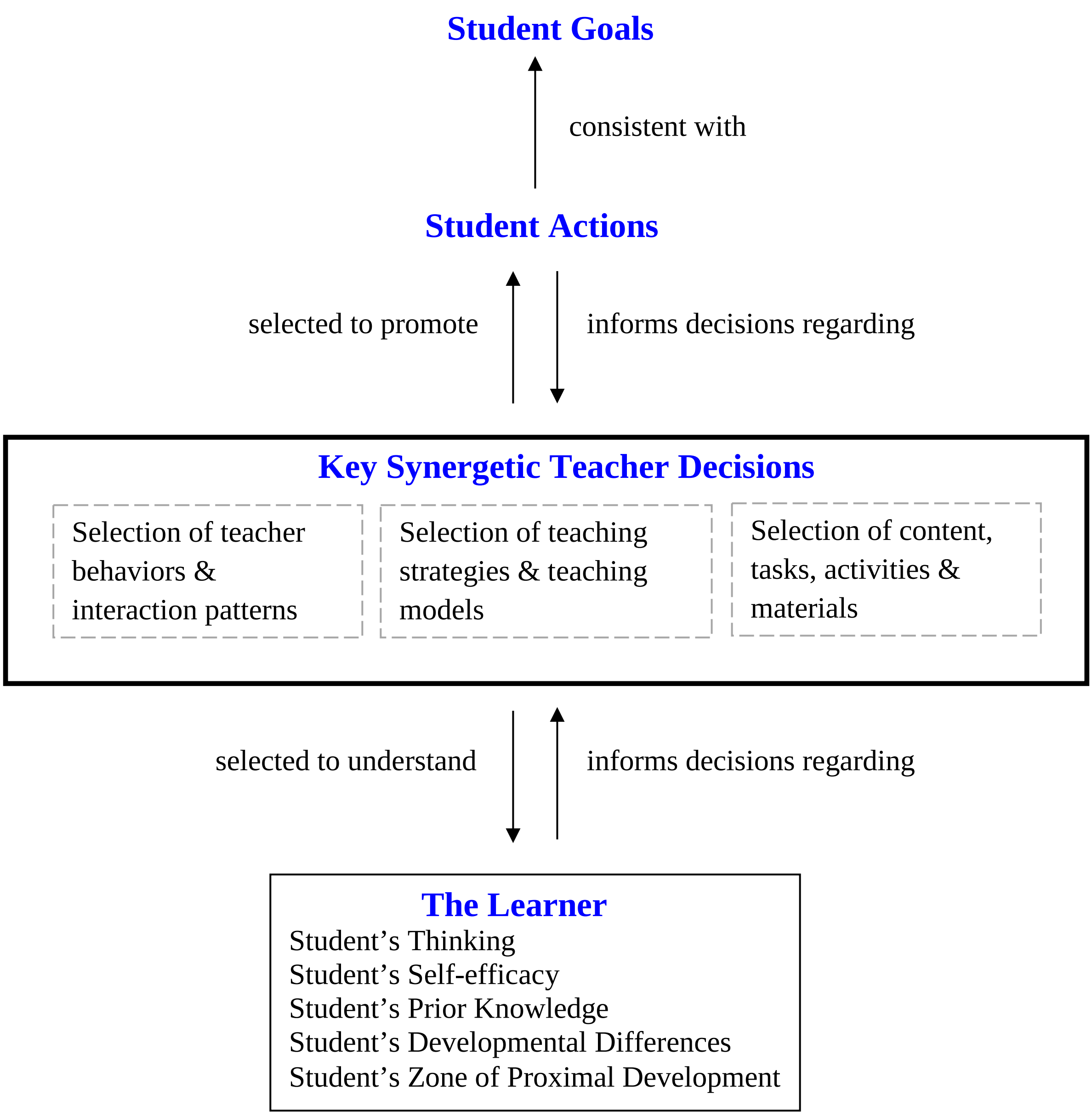
The complexity of teaching science through and as inquiry accounts, in part, for why it is relatively uncommon in science instruction. All too pervasive science teaching practices such as lecturing and assigning textbook readings, worksheets, and cookbook activities (Banilower, Smith, Weiss, Campbell & Weiss, 2013; Weiss, 1993; Weiss, Pasley, Smith, Banilower & Heck, 2003;) reduce the complexities of teaching by severely constraining students' thinking, decision-making, and input into a lesson. The consequence of these ubiquitous practices is that students have poor to inaccurate understanding of science concepts, and possess misconceptions regarding the characteristics of science and scientists.

Effectively teaching science through and as inquiry is complex, yet crucial for promoting goals like those appearing in Table 1. In the second article in this series (Clough, 2015), attention was drawn to key synergistic decisions appearing in Figure 1 and that those decisions should be deliberately made in light of desired student goals, how students learn, and relevant education research. That article addressed the multifaceted nature of making wise decisions regarding what content to teach, and what activities, tasks and materials to implement. This article addresses crucial decisions regarding the selection of teaching models and strategies and how what teachers do in a lesson (their behaviors and resulting interaction pattern) is most important for assisting students in making sense of what they study and for promoting the characteristics of science and scientists.

Table 1. Goals for science education

- Demonstrate deep robust understanding of fundamental science concepts.
- Exhibit an accurate understanding of the nature of science.
- Exhibit an accurate understanding of the nature of technology and engineering.
- Identify and solve problems effectively.
- Be creative and curious.
- Use critical thinking skills.
- Use communication and cooperative skills effectively.
- Actively participate in working towards solutions to local, national, and global problems.
- Set goals, make decisions, and accurately self-evaluate.
- Access, retrieve, and use existing scientific knowledge in the process of investigating phenomena.
- Convey self-confidence and a positive self-image.
- Demonstrate an awareness of the importance of science in STEM and STEM-related careers.

Figure 1. Framework Illustrating Teacher Decisions and their Interactions (Clough *et al.*, 2009)



FEATURES OF TEACHING THAT PROMOTE CHARACTERISTICS OF SCIENCE AND SCIENTISTS

Selection of teaching models and strategies

Teaching models can assist teachers in structuring lessons in a manner that reflect how students learn and promote desired goals for students. The learning cycle (Abraham, 1997) and its variants (e.g., 5-E model, Bybee, 1997), search, solve, create and share (SSCS) (Pizzini, Shepardson & Abell, 1989), and the science writing approach (Keys, Hand, Prain, & Sellers, 1999) are particularly helpful for structuring lessons to promote understanding science concepts and the characteristics of science and scientists. Many teaching models exist, but should be carefully selected as not all are well-suited for promoting the goals appearing in Table 1 (e.g., Hunter Lesson Design, Berg & Clough, 1991).

Teaching strategies (e.g., cooperative groups, think-pair-share, predict-observe-explain, and having students write on white-boards to express their ideas and thinking) are techniques and methods that may be used in any lesson irrespective of the overarching teaching model employed. Like teaching models, a plethora of teaching strategies exist, many which are questionable in light of how students learn and the goals appearing in Table 1. Thus, the selection of teaching strategies should be carefully considered and thoughtfully made in order to stimulate student thinking, expression of their ideas and reasoning before, during and after instruction, and assist in scaffolding students' thinking to desired understandings.

Interactions with students: The central core of effective teaching

Teaching science through inquiry is more complex because through that approach students' ideas and thinking spill out into the classroom. Ironically, this increased complexity sets the stage for promoting deeper conceptual understanding because in expressing their ideas and thinking, students are more mentally engaged and teachers begin to understand and thus can better respond to students' misunderstandings. Teachers must deliberately create interactions with students (at times in a whole class setting and at other times in small groups or individually with students) that draw out students' thinking. As students express their ideas and rationale for them, teachers must think of questions or experiences that will help students develop desired understandings. These crucial decisions must often be made on the fly in the act of teaching. No wonder so many science teachers find that teaching science through and as inquiry is a daunting undertaking.

Education literature too often conveys vague characterizations of the science teacher's role in inquiry. Ambiguous descriptions (e.g., facilitator, guide at the side, and providing students opportunities to construct ideas) obscure the importance of research-based decision-making and teacher behaviors crucial for shaping classroom experiences that promote desired science education goals. Teaching models and strategies, even when wisely selected, are only effective if teachers interact with students in a manner that assists them in sense-making (Weiss et al., 2003). For example, Southerland, Kittleson, Settlage and Lanier (2005), in a study of a third-grade classroom, reported that:

> ...despite a school year of learning cycle-based lessons, conceptual discussions about the physical phenomena the students were exploring occurred only in the presence of an instructor probing them for explanations. ...If the students were to make sense of this activity so that it bore a resemblance to a scientific understanding, then the teacher's monitoring and shaping of ideas and observations became necessary. (pp. 1043–1044)

This shaping of ideas is notoriously difficult, and demands attention to key teacher behaviors that include questioning, wait-time, inquisitive and encouraging non-verbal behaviors, attentive and diagnostic listening, and effectively responding to what students say and do to help them move progressively to desired ends.

To begin, intellectually engaging questions stimulate and focus students' thinking, encourage them to express their ideas, and thus help teachers understand students' reasoning. Extended-answer and thought-provoking questions begin with "how", "what" and "to what extent" rather than "can," "did," or "will." This avoids "yes/no" and other dichotomous responses from students that stifle discussions and fail to draw out students' thinking that would then be used to make further instructional decisions.

Also crucial is initiating questions at an appropriate level of difficulty and then scaffolding to more challenging questions that help students make desired connections. This is necessary to avoid intimidating students and stifling interaction, but also for helping students move from their current thinking to accepted science ideas. Several classification systems for questions exist, but most of these are based on a taxonomy of cognitive objectives introduced by Bloom et al. (1956). Penick, Crow & Bonnstetter (1996) suggested a questioning strategy particularly suited to inquiry science teaching that emphasizes students' prior experiences and using these experiences to build relationships, apply knowledge, and create explanations (Table 2).

Table 2. HRASE Questioning Hierarchy Suggested by Penick, Crow & Bonnstetter (1996)

History—questions that relate to students' experience:
- What did you do . . . ?
- What happened when you . . . ?
- What happened next . . . ?

Relationships—questions that engage students in comparing ideas, activities, data, etc.:
- How does this compare to . . . ?
- What else does this relate to . . . ?
- What do all these procedures have in common?

Application—questions that require students to use knowledge in new contexts:
- How could this idea be used to design . . . ?
- What recognized safety issues could this solution solve?
- What evidence do we have that supports . . . ?

Speculation—questions that require thinking beyond given information:
- What would happen if you changed . . . ?
- What might the next appropriate step be?
- What potential problems may result from . . . ?

Explanation—questions that get at underlying reasons, processes, and mechanisms:
- How does that work?
- How can we account for . . . ?
- What justification could be provided for . . . ?

While effective questioning will not always begin at the lowest taxonomic level nor occur in a prescribed linear sequence (Good & Brophy, 1994), attending to a question's level of difficulty and carefully scaffolding questions are critical for promoting mental engagement and student participation. Asking questions that accurately diagnose students' thinking, effectively help students accurately assess their thinking, and move students towards desired conceptual understanding is extremely challenging. Weiss et al. (2003) reported that this kind of effective questioning is relatively rare in United States mathematics and science classes. Accurately determining where students' thinking lies, and establishing a sequential series of questions and/or experiences necessary that effectively scaffold students' understanding to accepted science ideas demands from teachers a very deep understanding of science content (Tobin & Garnett, 1988) and science pedagogy that must be applied in the act of teaching!

The role of effective questioning in engaging students and revealing their thinking may seem rather obvious. The role of questions in science education to help students make desired connections is just as important, but not so evident (Olson, 2007; Weiss et al., 2003). However, questioning is crucial for helping students see problems with their current conceptions and build more accurate science ideas. For example, consider an interaction that took place years ago between me and one of my high school chemistry students.

Several weeks prior to the dialogue described below, the student and his classmates had successfully completed a series of inquiry activities investigating the characteristics of chemical changes, including the conservation of mass (e.g., Clough & Clark, 1994a). In that laboratory inquiry experience, chemicals react in a closed baggie and produce a gas that fills the baggie. Students determine that the mass of the system (baggie and enclosed chemicals) decreases as the reaction occurs, and almost always wrongly attribute this to a gas being formed. The idea that gases have no mass is a common misconception (Stavey, 1990). Through teacher questioning and student testing of their ideas in response to those questions, students determine that the gas formed in the chemical reaction leaks from even a zipped baggie. Students then exert significant thought and creativity in their efforts to stop the escape of the gas produced. With each sequential improvement, the mass "loss" due to gas leaking out of the system became smaller. Through this approach, students came to the conclusion that if perfect conditions existed (e.g., no substances lost/gained by the system, perfect balance, etc.) that mass would remain exactly the same before and after a chemical reaction.

For several weeks afterwards, a variety of activities and discussions took place addressing typical chemistry content such as balancing chemical reactions, the mole concept, and stoichiometry—all which the student in question appeared to understand. Now, students were enthusiastically attempting to determine the products of that prior chemical reaction (Clough & Clark, 1994b) using all that they had previously learned in the chemistry course to that point. Several days into this activity, the student in question approached me, and the following conversation ensued:

Student:	Mr. Clough, the mass of my system went down.
Me:	How do you account for that?
Student:	A gas was formed and gases have no mass.
Me:	(Maintaining an accepting and inquisitive appearance.) What do you think gases consist of?
Student:	Atoms.
Me:	What do you know about atoms and mass?
Student:	Atoms have no mass.
Me:	(Still maintaining an accepting and inquisitive appearance, but searching for a way to help the student see his misunderstanding.) From a chemical perspective, what are you made up of?
Student:	Atoms. (The student paused with a paradoxical look on his face.) And I have mass.

This illustrates the most complex and unpredictable portion of teaching—interacting with students to better understand their thinking and help them create intended meanings. In this particular interaction (only one among many in any class) the student initiated the interaction with a statement about something he had noted in the laboratory. Rather than interpret the phenomenon for the student, I posed a question to have him elaborate on his statement. The student shot back an incorrect answer (i.e., "gases have no mass"), a misconception that is common and persistent among students (Stavey, 1990). Using non-judgmental, but encouraging non-verbal behaviors, I continued the interaction keeping in mind the need to listen intently to my student's thinking, acknowledge his ideas without judging them, and respond with questions that played off his thinking. Quite often, our interaction with students during inquiry activities is where we get an accurate picture of what they really think. Questioning is key for teasing out what students really think, helping them see the inadequacy of misconceptions, and piecing together a more accurate understanding.

Unfortunately, teachers who improve their questioning are often frustrated when student interaction does not immediately increase. The initial novelty may puzzle students, but other factors under a teacher's control also may be hindering students' engagement. While questions set an academic mood, they alone do not encourage students to ponder and respond. Thought-provoking questions require time for thinking, yet teachers often wait less than one second after asking a question before moving on in some manner that conveys to students they need not respond (Rowe, 1974a).

Waiting at least three seconds (often more) after having asked a question (called wait-time I) along with waiting a few seconds after students answer a question (called wait-time II) has been shown to result in the following desirable outcomes (Rowe, 1974a, 1974b, Rowe, 1986):

- the length of student responses increases by 700%;
- the number of unsolicited, but appropriate, student responses increases;
- failures of students to respond decreases;
- students' confidence, as reflected in decrease of inflected responses, increases;
- the incidence of speculative student responses increases;
- more student inferences are supported by evidence and logical argument;
- the incidence of student-student comparisons of data increases;
- the number of student questions and proposed experiments increases; and
- the incidence of responses from students rated by teachers as relatively slow increases.

Because students are expressing more of their thinking that a teacher may use in further questioning, and because teachers have more time to think, wait-time also helps improve teachers' questioning. Keeping quiet at appropriate times is imperative in creating an environment that facilitates significant student involvement and helps achieve a number of desired student goals.

However, even these teacher behaviors may not encourage the extensive interaction between teacher and students that is so important for learning. Students often feel uncomfortable answering a teacher's questions, particularly in front of peers. Encouraging student responses to questions demands, in part, exhibiting a number of encouraging non-verbal behaviors alongside appropriate questions and wait-time. Body language communicates how open a teacher is to student responses. Teachers who genuinely want student interaction will appropriately incorporate encouraging and expectant non-verbal behaviors such as smiling, appropriate eye-contact, movement around the room and among students, leaning forward when students are speaking, raising eyebrows to show interest, inviting hand-gestures (Bavelas, Chovil, Coates & Roe, 1995; Roth, 2001), equality of physical status, and wait-time I and II.

However, sensitively responding to what students say is also crucial. Instead of overtly judging the responses put forth by students, teachers should acknowledge students' ideas, seek elaboration, and ask questions that help students move to the accepted science idea. These teacher behaviors (illustrated in the dialogue presented earlier) emphasize reasoning and justification for ideas (correct or incorrect), while at the same time move students to desired scientific understanding.

Implemented together, effective questioning, encouraging non-verbal behaviors, appropriate wait-time I and II, listening attentively, and responding in a manner that further engages students are the central core of effective teaching (Clough, 2003). Clough, Berg & Olson (2009) note that these teacher behaviors:

> ...are the essential "tools" teachers always have at that their disposal for understanding students' thinking, promoting student understanding of content, and advancing student learning. Moreover, it emphasizes that teaching is, above all else, an activity centered on human interaction that requires simultaneous attention to several crucial teacher behaviors. (p. 830)

Teaching matters!

Teacher questioning and other behaviors significantly impact student learning (Banilower, Cohen, Pasley & Weiss, 2010; Shymansky & Penick, 1981; Tobin and Garnett, 1988; Weiss et al., 2003)! The misconceptions regarding science and the nature of science that students bring to science instruction along with the counter-intuitive nature of many science ideas (Cromer, 1993; Matthews; 2015; Wolpert, 1992) and the complex nature of learning necessitates that teachers interact with students in ways that assist them to "see" the natural world in new, exciting, and powerful ways. Promoting the characteristics of science and scientists is a complex undertaking, and education literature too often gives the mistaken impression that good inquiry activities and strategies alone are sufficient for effective teaching and learning. When teaching science through and as inquiry, the teacher's role in student learning is far more critical, for without well-reasoned teacher intervention, students will become frustrated as they alone will rarely create meaning similar to that of the scientific community. Even the best inquiry science activities will not by themselves effectively help students reach the important goals appearing in Table 1. The features of teaching that promote these goals are themselves complex and counter-intuitive, and the next and final article in this series will address what is required to prepare teachers to implement such practices.

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References

Abraham, M. R. (1997). The learning cycle approach to science instruction. Research matters – to the science teacher, No. 9701. National Association for Research in Science Teaching (NARST). http://www.narst.org/publications/research/cycle.cfm Retrieved May 30, 2015.

Banilower, E., Cohen, K., Pasley, J. & Weiss, I. (2010). *Effective science instruction: What does research tell us?* Second edition. Portsmouth, NH: RMC Research Corporation, Center on Instruction.

Banilower, E., Smith, P. S., Weiss, I., Malzahn, K., Campbell, K., & Weis, A. (2013). *Report of the 2012 national survey of science and mathematics education.* Chapel Hill, NC: Horizon Research, Inc.

Bavelas, J. B., Chovil, N., Coates, L. & Roe, L. (1995). Gestures specialized for dialogue. *Personality and Social Psychology Bulletin*, 21, 394–405.

Berg, C. A. & Clough, M. P. (1991). Hunter lesson design: The wrong one for science teaching. *Educational Leadership*, 48(4), 73-78.

Bloom, B., Englehart, M. Furst, E., Hill, W., & Krathwohl, D. (1956). *Taxonomy of educational objectives: The classification of educational goals. Handbook I: Cognitive domain*. New York, Toronto: Longmans, Green.

Bybee, R. (1997). *Achieving scientific literacy: From purposes to practices.* Portsmouth, NH: Heineman.

Clough, M. P. (2015). A Science Education that Promotes the Characteristics of Science and Scientists: Features of content, activities and materials. *K-12 STEM Education*, 1(2), 65-73.

Clough, M. P. (2003). Understanding the complexities in learning and teaching science: The value of a research-based framework. Association for Science Teacher Education (ASTE) International Conference, St. Louis, MO, January 29 - February 2.

Clough, M. P., Berg C. A. & Olson J. K. (2009). Promoting effective science teacher education and science teaching: A framework for teacher decision-making. *International Journal of Science and Mathematics Education*, 7(4) 821-847.

Clough, M. P. & Clark, R. L. (1994a). Cookbooks and constructivism: A better approach to laboratory activities. *The Science Teacher*, 61(2), 34-37.

Clough, M. P. & Clark, R. L. (1994b). Creative constructivism: Challenge your students with an authentic science experience. *The Science Teacher*, 61(7), 46-49.

Cromer, A. (1993). *Uncommon sense: The heretical nature of science*. New York: Oxford University Press.

Good, T. L. & Brophy, J. E. (1994). *Looking in classrooms*, 6th edition. New York: HarperCollins.

Keys, C. W., Hand, B. M., Prain, V. R. & Sellers, S. (1999). Rethinking the laboratory report: Writing to learn from investigations. *Journal of Research in Science Teaching*, 36(10), 1065-1084.

Leinhardt, G. & Greeno, J. G. (1986). The cognitive skill of teaching. *Journal of Educational Psychology*, 78(2), 75-95.

Matthews, M. R. (2015). *Science teaching: The contribution of history and philosophy of science*. 20th Anniversary revised and expanded edition. New York: Routledge.

Olson, J. K. (2007). Preservice teachers' thinking within a research-based framework: What informs decisions. *International Journal of Science and Mathematics Education*, 5(1), 49-83.

Penick, J. E., Crow, L. W. & Bonnstetter, R. J. (1996). Questions are the answer: A logical questioning strategy for any topic. *The Science Teacher*, 63(1), 27–29.

Pizzini, E.L., Shepardson, D.P. & Abell, S.K. (1989). A rationale for and the development of a problem solving model of instruction in science education. *Science Education*, 73, 523-534.

Roth, W. M. (2001). Gestures: Their role in teaching and learning. *Review of Educational Research*, 71, 365–392.

Rowe, M. B. (1974a). Wait-time and rewards as instructional variables, their influence on language, logic, and fate control: Part I—wait-time. *Journal of Research in Science Teaching*, 11, 81-94.

Rowe, M. B. (1974b). Relation of wait-time and rewards to the development of language, logic, and fate control: Part II—rewards. *Journal of Research in Science Teaching*, 11, 291-308.

Rowe, M. B. (1986). Wait-time: Slowing down may be a way of speeding up. *Journal of Teacher Education*, 37, 43-50.

Shymansky, J.A. & Penick, J.E. (1981). Teacher behavior does make a difference in hands-on science classrooms. *School Science and Mathematics, 81*, 412-422.

Southerland, S. A., Kittleson, J., Settlage, J. & Lanier, K. (2005). Individual and group meaning-making in an urban third grade classroom: Red fog, cold cans, and seeping vapor. *Journal of Research in Science Teaching*, 42, 1032–1061.

Stavy, R. (1990). Children's conception of changes in the state of matter: From liquid (or solid) to gas. *Journal of Research in Science Teaching*, 27(3), 247-266.

Tobin, K. & Garnett, P. (1988). Exemplary practice in science classrooms. *Science Education*, 72, 197–208.

Weiss, I. R. (1993). Science teachers rely on the textbook. In Yager, R.E. (Ed.) *What research says to the science teacher, volume seven: The science, technology, society movement*. Washington, D.C.: National Science Teachers Association.

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.

Wolpert, L. (1992). *The unnatural nature of science*. Cambridge, MA: Harvard University Press.