Experimental inquiry in introductory physics courses

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Physics teacher educators following national science teacher preparation guidelines will both employ and promote the use of experimental inquiry during instruction. In order for in-service physics teachers to use this form of scientific inquiry appropriately, it is important that they possess a basic understanding of the content, nature, and history of science. Indeed, it is imperative for physics teacher educators and their teacher candidates to have a thorough understanding of experimental inquiry so that they come to value it, are more likely to practice it properly, and understand how to help students achieve a higher degree of scientifically literacy.

The effective use of scientific inquiry is one hallmark of outstanding science teachers. Science teachers who use this approach develop within their students an understanding that science is both a product and a process. Not only do the students of these teachers learn the rudimentary knowledge and skills possessed and employed by scientists, they also learn about the history and nature of science including its nomenclature, intellectual process skills, rules of evidence, postulates, appropriate dispositions, and major misconceptions (Wenning, 2006). Unfortunately, not all teacher candidates learn how to conduct inquiry and not all science teachers use inquiry in an effective fashion. Some in-service science teachers don't employ it at all; others know it but don't know how to teach it.

There are many reasons why established in-service science teachers fail to teach using inquiry (Costensen & Lawson, 1986). Among these reasons is that science teachers themselves often do not possess a holistic understanding of the scientific endeavor. This likely stems from the nature of traditional science teaching at the college and university levels that commonly uses a didactic — teaching-by-telling — approach. Many introductory courses rely on the use of equations to guide instruction at the cost of conceptual understanding. To many students, physics at the introductory level seems to be best characterized by the phrase "the search for the proper equation."

Little attention is given in some teacher education programs to how the processes of scientific inquiry should be taught and acquired. It is often assumed by physicists and physics teacher educators that once teacher candidates graduate from institutions of higher learning they understand how to conduct scientific inquiry and can effectively pass on appropriate knowledge and skills to their students. This is most often not the case.

Scientific inquiry processes, if formally addressed at all in the teacher preparation curriculum, are often treated as an amalgam of non-hierarchical activities. Wenning (2005, 2010, 2011) has synthesized a framework for more effective promotion of inquiry processes among students known as the Levels of Inquiry Model of Science Teaching. This article (in conjunction with previously published articles) is designed to help science teachers and teacher educators promote an increasingly more sophisticated understanding of experimental scientific inquiry among their students.

Conducting Scientific Inquiry in the Classroom

Just as in the statement that "not all that glitters is gold," not all science teaching in authentically inquiry oriented even though that might be the intent. Some teachers think that asking students lots of questions constitutes inquiry. Not so. Authentic scientific inquiry has specific characteristics. The reader can see that distinction in the following scenarios and in what follows.

Stephen is a student teacher at a local high school. He is nearing graduation with a degree in physics teaching, but comes from a university where didactic teaching is indirectly promoted through his physics content courses, and inquiry teaching is ineffectively promoted during his science teaching methods courses. Stephen begins his lesson with the statement, "Today we are going to learn about the law of reflection." He starts off asking lots of background questions and then tells his students that light travels in a straight line. He goes on to note that when light hits a reflecting object such as a mirror, there is a particular relationship between the angle of incidence and the angle of reflection. He talks about the normal line, and how the angles of incidence and reflection are measured relative to the normal line. He then uses a bright green laser pointer in a darkened room to demonstrate this phenomenon. Finally, he states, "You see, the angle of incidence equals the angle of reflection."

Fatima is also a student teacher. She is also about to graduate from the same physics teacher education program where now, years later, inquiry practice is promoted indirectly through content courses and the associated laboratory activities, and both directly and effectively in science teaching methods courses. She begins her class by providing students with plane mirrors and two different colored threads emanating from a point at the base of the mirror. She tells the students to pull one string and hold it in place with a pushpin located near its end. She then tells the students to arrange the other string in such a way that it lines up with the image of the first string as seen in the mirror. She directs the students to look into the mirror along the line of sight of the second string. What do they see? The image of the pushpin! Fatima asks, "Why do you see the image of the pushpin?" The students reply, "Because light from the pushpin hits the mirror, and is reflected to our eyes along the path of the thread." The path of the light thus being established as a straight line, students are asked to draw a line perpendicular from the mirror at the point where the two strings converge, and to measure the angle of the incoming and outgoing light rays from the normal. Fatima then asks the students, "What is the relationship between the angles of the incoming and outgoing light rays?" They respond that the two angles are equal.

The key difference between these two student teachers and their lessons is substantial. In Stephen's case, he is teaching by telling and merely asking students to watch as he confirms what he has said. In Fatima's case, she is helping students to construct knowledge from their own experiences. These differences may well result from different understandings of what the phrase "scientific inquiry" actually means. Only by having a clear expectation of both teacher and student performance can one objectively say whether or not a teacher's practice is inquiry oriented.

Defining Scientific Inquiry

Scientific inquiry has been variously defined. For instance, the National Research Council in *National Science Education Standards* defines scientific inquiry as follows:

> Scientific inquiry refers to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. Inquiry also refers to the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world. (NRC, 1996, p. 23)

The American Association for the Advancement of Science Project 2061 gives a slightly different definition in *Benchmarks for Science Literacy*:

> Scientific inquiry is more complex than popular conceptions would have it. It is, for instance, a more subtle and demanding process than the naive idea of "making a great many careful observations and then organizing them." It is far more flexible than the rigid sequence of steps commonly depicted in textbooks as "the scientific method." It is much more than just 'doing experiments,' and it is not confined to laboratories. More imagination and inventiveness are involved in scientific inquiry than many people realize, yet sooner or later strict logic and empirical evidence must have their day. Individual investigators working alone sometimes make great discoveries, but the steady advancement of science depends on the enterprise as a whole. (AAAS, 1993, p. 9).

The National Science Teachers Association defines scientific inquiry somewhat differently still:

> Scientific inquiry is a powerful way of understanding science content. Students learn how to ask questions and use evidence to answer them. In the process of learning the strategies of scientific inquiry, students learn to conduct an investigation and collect evidence from a variety of sources, develop an explanation from the data, and communicate and defend their conclusions (NSTA, 2004, p. 1).

While such statements are correct — and several specific examples of scientific inquiry are given in the associated texts — these broad characterizations and the associated examples are of little help to science teachers and teacher candidates who are looking for a detailed operational definition that can serve as a guide for inquiry-oriented instruction.

Basic Types of Scientific Inquiry

There are many types of scientific inquiry – about as many as there are scientists – but at the most fundamental level these types can be reduced to four: observational, computational, theoretical, and experimental. Still, none of these four can be said to be entirely independent of the others.

Astronomy is an example of what is primarily an observational science. Stars and galaxies cannot be brought into a laboratory for analysis; therefore, variables cannot be manipulated to see the outcome. Scientists apply laws of physics derived from laboratory study to determine the size, temperature, electron density, magnetic field strength, rotation, and other conditions prevailing on the surface. Mathematical processes can be used to model stellar systems from binary stars to star clusters to galaxies.

Scientific modeling based on mathematics (the "queen of sciences" according to Gauss) is a good example of computational scientific inquiry. Models are constructed and modified until they work analogously to real-world systems. Of course, agreement with existing external observations does not necessarily imply that a model is consistent with reality. Only with additional experimental procedures or observations can that conclusion be drawn.

Hypothesis development and testing constitute the major processes of theoretical inquiry. Induction and deduction are part and parcel of what many physicists do today. A study of the history of modern physics shows how the major ideas concerning the structure of the atom were developed and tested.

Experimental sciences allow for the controlled testing of independent variables, changes in dependent variables, and with the use of mathematical processes the analysis of the data. Physics is perhaps the preeminent experimental science as it is among the best suited for teaching experimental procedures in the classroom. Physics provides classroom opportunities for experimental manipulation and visualization and graphing, principle and law production. These are not as readily available in studies of astronomical, chemical, biological, environmental, and earth sciences. The use of experimental inquiry in physics encompasses all forms inquiry in as much as observational, computational, and even theoretical processes can used in the planning, execution, analysis, and explanation of an experiment.

Experimental Inquiry in Introductory Physics

For the purpose of operationally defining experimental scientific inquiry at a level appropriate for introductory physics courses, the author provides an ordered listing of experimental skills necessary for conducting scientific inquiry in Table 1. While the listing in Table 1 might at first appear to be based on a rather naïve understanding of the nature of scientific inquiry, it was developed in light of works by Kneller, Bauer, Wynn, Popper, Gould, Root-Berstein, Sayer and a number of others whose writings have been included in *Science and Its Ways of Knowing* edited by Hatton and Plouffe (1997). The author is fully cognizant of the fact that "there is no scientific method", and that science more often than not develops along ways that are not consistent with the traditional Baconian approach.

Further, this listing was developed in light of the fact that physics at the secondary school level is generally not driven by hypothesis/theory development, but that typically data are collected for the purpose of formulating principles, developing empirical laws, or constructing models. Finally, this listing was prepared with the understanding that not all inquiry processes will be experimental in nature. Sometimes reason will be used to draw scientific conclusions on the basis of evidence. At other times scientific conclusions simply will be based on repeatable, verifiable observations.

Additionally, not all scientific inquiry skills will be used in any one investigation. Scientific inquiry based on observations will likely differ significantly from scientific inquiry based on experimentation or computation. Astronomers, geologist, biologists, chemists, and physicists all have different approaches to conducting scientific investigations and will use various elements of the listing to different degrees.

Table 1. *Framework providing an ordered listing of scientific inquiry skills inherent in introductory-level scientific inquiry. This framework is intended to be suggestive, not definitive.*

- Identify a problem to be investigated.
- If appropriate:
  - use induction to formulate a hypothesis or model incorporating logic and evidence.
  - use deduction to generate a prediction from the hypothesis or model.
  - design experimental procedures to test the prediction.
- Conduct a scientific experiment, observation, or simulation to gather data, test a hypothesis or substantiate a model:
  - Identify the experimental system
  - Identify and define variables operationally
  - Conduct a controlled experiment or observation
- Collect meaningful data, organize, and analyze data accurately and precisely:
  - Analyze data for trends and relationships
  - Construct and interpret a graph
  - Develop a principle using induction or a law based on evidence that uses graphical methods or other mathematic model
- Apply numerical and statistical methods to numerical data to reach and support conclusions:
  - Use technology and math during investigations
  - Apply statistical methods to make predictions and to test the accuracy of results
  - Draw appropriate conclusions from evidence
- Explain any unexpected results:
  - Formulate an alternative hypothesis or model if necessary
  - Identify and communicate sources of unavoidable experimental error
  - Identify possible reasons for inconsistent results such as sources of error or uncontrolled conditions
- Using available technology, report, display, and defend the results of an investigation to audiences that might include professionals and technical experts.

Characterizing Experimental Inquiry

Even with the framework for characterizing experimental scientific inquiry given in Table 1, some student teachers and in-service teachers might still not have a fully developed understanding of how scientific inquiry is done or taught. Studies of teachers new to inquiry-based instruction show that many novice candidates have misconceptions about inquiry and misunderstandings about the role of both teacher and students in inquiry-based instruction (Reif, 2008). Sometimes one or more non-examples can help to make clear what scientific inquiry is not. Some teachers think that having students respond to lots of questions constitutes inquiry. They ask questions that lead students in a stepwise fashion to a particular solution. This funneling type of questioning (Wood, 1998) does not constitute authentic inquiry. Scientific inquiry is NOT a teacher asking lots of questions, and neither is having students solve "puzzle problems" at the end of a textbook chapter, looking up vocabulary definitions, or completing worksheets. Neither is inquiry letting students run wild without the benefit of a curriculum or instruction.

Rankin (2000) points out that there are a number of strongly held misconceptions related to inquiry-oriented instruction. Among these are the following:

- *Misconception: Inquiry-oriented instruction is an either/or proposition* — While proponents of inquiry often promote it to the exclusion of didactic methods, this is not to suggest that inquiry is an all-or-nothing proposition. In an effort to adequately address the depth-versus-breadth problem, it is appropriate to provide roughly equal amounts of instruction that are inquiry oriented and didactic. Approaches such as lectures, readings, discussions, demonstrations, videos worksheets, problem sets, and such do have their place even in an inquiry-oriented classroom. Didactic approaches will help students address the broader content of science while inquiry approaches will help students better learn the processes of science. More often than not, available instructional materials determine which topics are taught in depth and which in breadth in the typical science classroom.

- *Misconception: All hands-on activities constitute inquiry; all inquiry activities are hands-on* — Not all hands-on activities constitute inquiry. For instance, students following step-by-step instructions to perform a laboratory activity in cookbook fashion might appear to be doing inquiry, but they are merely following instructions that overtly mimic inquiry. Students following a set of cookbook-like instructions rarely come to understand the inquiry process. Students can conduct different types of inquiry, only some of which require working with materials. Developing hypotheses or models, for instance, are intellectual processes that are part of scientific inquiry but that do not necessarily require the use of manipulatives. Inquiry allows students to identify questions, and develop and follow their own procedures to answer those questions. Teachers need to be aware of the fact that much of the inquiry process occurs both before "doing" a lab, as well as after. The actual hands-on components aren't always the most important parts.

- *Misconception: A dichotomy exists between content and process* — Science is a combination of both process and product; it is a way of constructing knowledge from experience. To separate ways of knowing from the knowledge itself is, in effect, to teach on the basis of mere belief. Science teaching based on authority is more akin to preaching than teaching. Effective science teachers will often move back and forth between practices that emphasize one approach over the other in order to provide sufficient understanding of both the processes and products of science.

- *Misconception: Inquiry teaching is chaotic* — Appropriate inquiry teaching is often structured. In these cases, the teacher prepares conditions under which students can best learn. The teacher is seen as a mentor, a facilitator of learning, and not as a wise sage who provides answers to all student questions. Students take responsibility for their own learning. Teachers help students develop their own understandings, and address their misunderstandings. During inquiry processes, teachers will move around the classroom assisting students in making clarifications, and asking questions that can lead students to a fuller understanding of the subject matter.

Fortunately, the *National Science Education Standards* (NRC, 1996) gives a detailed explanation of what it means to teach using inquiry when they characterized the actions of both teachers and student.

The teacher:

- presents lessons that are student-centered (teacher builds on knowledge students bring to or develop from the learning situation; teacher helps students construct meaning from experiences; focus on student as active inquirer rather than passive receiver of knowledge).
- focuses on one or more questions as the active mode of inquiry (lesson, many guiding questions; lab, one guiding question).
- encourages student thinking and questioning
- engenders debate and discussion among students
- provides a variety of levels and paths of investigation
- is a mentor and guide, giving as little direction as possible
- shows an active interest in students and promotes an active quest for new information and ideas.
- avoids appeals to authority and avoids acting as an authority figure
- maintains a classroom atmosphere conducive to inquiry
- places emphasis on "How do I know the material of this course?" rather than "What must I know in this course?"
- uses appropriate questioning skills such as wait time, variety, distribution, and formulation
- responds appropriately to what students have to say or do that contributes to lesson

The students:

- make observations and collect data
- formulate predictions based on observations and create and conduct experiments in order to validate conclusion
- work out relationships of cause and effect.
- relate independent and dependent variables to establish meaningful relationships.
- use reasoning ability
- make decisions and draw conclusions on the basis of data
- defend conclusions on the basis of data
- interpret collected data or observations.
- devise their own way to report their findings to class members.

Teaching via experimental inquiry is one of the backbones of the current science education reform movement. While some teacher candidates and in-service science teachers might be skeptical of the use of inquiry as an effective instructional practice, or dismiss it because it reduces the amount of content that can be "covered" (a word that, ironically, means to hide from view), a strong case can be made for incorporating inquiry practice into day-to-day science instruction. Every teacher educator, every teacher candidate, and every in-service teacher should be fully cognizant of the case that can be made in favor of incorporating inquiry into the practices of science instruction.

Making the Case for Scientific Inquiry

A strong case can be made on behalf of teaching science using inquiry. The points below stem from sources as diverse as Francis Bacon's *Novum Organum* of 1620 (Anderson, 1985), *Goals of the Introductory Physics Laboratory* (AAPT, 1998), and *Inquiry and the National Science Education Standards* (NRC, 2000). Among the key philosophical arguments and research-based claims that can be made in favor of inquiry-oriented instruction are the following: *Through inquiry-oriented instruction,*

1. *students learn about science as both process and product*. Understanding science consists of more than just knowing facts or being able to find and solve the proper equations. An authentic science education will help students understand what is known as well as how it is known. Like the first true scientists, we reject Aristotelian scholasticism that would have us learn on the basis of the authority of others rather than from scientific observations, experiments, calculations, and critical thinking. Properly constructed inquiry-oriented laboratory activities will include some opportunities for designing investigations that engage students in important hands-on, minds-on experiences with experimental processes. As with any well-rounded education, we should seek to teach our students how to think rather than what to think.

2. *students learn to construct an accurate knowledge base by dialoguing*. Regardless of the type of classroom instruction, a student will build new knowledge and understanding on what is already known and believed. Students do not enter the classroom with minds that are *tabulae rasae* — blank slates — as philosopher John Locke first suggested. Rather, students come to a classroom with preconceived notions, not all of which are correct. In the inquiry-based classroom, students formulate new knowledge by either replacing or modifying and refining their current understanding. In an inquiry-oriented classroom, the quality of classroom discourse is dramatically improved with the use of such things as whiteboards and Socratic dialogues (Wenning, 2005; Wenning, Holbrook & Stankevitz, 2006). Teachers conducting Socratic dialogues come to understand what students know, and can identify, confront, and resolve preconceptions that limit students' understanding.

3. *students learn science with considerable understanding.* Rather that merely memorizing the content of science only to be rapidly forgotten, students learning science through personal experience learn with increased conceptual understanding. Appropriate classroom and laboratory activities help students master basic physics concepts. Experiential learning results in prolonged retention, and refines students' critical thinking and problem-solving skills helping them improve standardized test scores. A deep understanding of subject matter is critical to the ability to apply knowledge to new situations. The ability to transfer learning to new situations is strongly influenced by the extent to which students learn with understanding. Learning via inquiry is learning that lasts, and not learning that merely suffices for the demands of schooling – passing a test.

4. *students learn that science is a dynamic, cooperative, and accumulative process.* The work of scientists is mediated by the social environment in which they interact with others; the same is true in the inquiry-oriented science classroom. Directly experiencing natural phenomena and discussing results helps students understand that science is the work of a community of real people, and that "genius" in science does not always matter — great progress can be made following the accumulation of many small steps. While the process of inquiry is slower than direct instruction, with its sometimes non-linear approach (allowing for the detection and correction of mistakes) it is more realistic and gives a better understanding to students of the social context of science. Only in cooperative settings such as laboratory work can students develop collaborative learning skills that are critical to the success of so many real-world endeavors. Science might be thought of as a process of developing knowledge by consensus. Disagreements must be worked out between students. The teacher is not viewed as the ultimate "authority" in a true inquiry-oriented classroom.

5. *students learn the content and values of science by working like scientists.* The way we educate our students has profound implications for the future. We can encourage them to show submission of intellect and will thereby indoctrinating them to become uncritical consumers of information, or we can help them learn the nature and values of science thereby gaining a scientific worldview. Do we not want to graduate students who are rational and skeptical inquirers rather than intellectual plebiscites? Of course we do, and inquiry-oriented instruction is one way to achieve it. Using such instructional practices, student learn comes directly from experience. The inquiry approach avoids presumptive authority, and inculcates students with a healthy skepticism. Inquiry-oriented instruction helps students confront pseudoscience by arming them with the skeptical, rational philosophy of Bayle, Bacon, Pascal, Descartes, and Locke.

6. *students learn about the nature of science and scientific knowledge.* Students come to know how scientists know what they know. They learn to adopt a scientific epistemology. Students are moved from uncritical belief to an informed understanding based on experience. Inquiry-oriented instruction helps students to understand the role of

direct observation, and to distinguish between inferences based on theory and on the outcomes of experiments. Inquiry-oriented laboratory work helps students develop a broad array of basic tools of experimental science, as well as the intellectual skills of critical thinking and problem solving. Students learn to use nature itself as the final arbiter of claims.

7. *students can come together in cooperative groups to develop the mental operations and habits of mind that are essential to developing strong content knowledge, appropriate scientific dispositions, and an understanding of both the nature of science and scientific knowledge.* The importance of cooperative learning cannot be overstated in helping students develop the abilities of scientific inquiry—either in the laboratory working on an experiment or in a classroom working on an Internet-based research project. Cooperative learning also contributes significantly to advancing a more comprehensive form of scientific literacy. Students working in cooperative groups can attack and solve more complex laboratory and real-world problems than they could do individually. Cooperative work frequently results in more and better solutions to such problems. Communities of learners commonly demonstrate a deeper understanding of the problem being addressed, how to solve it, and the meaning and significance of the solution. Learning communities provide students with the opportunity to "talk science" in a comfortable setting, share their understanding without needless criticism, and clarify their thinking through peer communication without embarrassment. Each student can practice problem-solving and critical-thinking skills in a relatively safe environment until they become individually more proficient.

8. students can receive the motivation they need to learn science and pursue science-related careers. Actively learning science content through first-hand experiences is much more interesting for students when compared to passively accepting it as "received wisdom". Inquiry-oriented instruction can serve as an important motivational tool for getting students to consider careers in the sciences and help to maintain classroom discipline. Students who experience the joy and wonder of creativity and discovery are more likely to pay attention in class and become scientists (or science buffs) than perhaps through any other process.

Teacher educators, teacher candidates, and in-service teachers need to realize that scientific inquiry is suitable for use and as subject matter for study at all grade levels. Only when a science teacher understands essential concepts, methods of inquiry, use of technology, structure of science and the science disciplines can he or she create meaningful learning activities for students. Teachers cannot share what they themselves do not possess. Additionally, teachers should be aware that students often do not come to understand scientific inquiry processes merely through "example." Teachers can help students learn about scientific inquiry processes both implicitly and explicitly using inquiry-oriented instruction. Students will learn more by directly speaking with the teacher and each other about the nature of scientific inquiry, its tenets and assumptions, and processes and products in comparison to soaking it up on their own through "osmosis" (Wenning, 2006).

Approaches to Experimental Inquiry

As a study of the history of science shows, there are many approaches to scientific inquiry. Scientific inquiry can range from making passive observations of a natural phenomenon, to finding the relationship between two variables in a controlled experiment, to something as complex as developing and testing hypotheses or models in an attempt to find out why a particular relationship between two variables holds.

The Physics and Astronomy Education Research (PAER) Group at Rutgers University has identified three forms of experimental inquiry that would be appropriate to many middle and high school physical science classrooms: (a) an <u>observation experiment</u> used to investigate a new phenomenon such as determining if there is a relationship between pressure and temperature of a gas when its volume is kept constant, (b) a <u>testing experiment</u> used to test a hypothesis or model such as whether or not an object always moves in the direction of the net force exerted upon it, and (c) an <u>application experiment</u> used to solve a practical problem or determining a physical quantity such as finding the coefficient of static friction between two surfaces.

While these are suitable types of inquiry for middle and high school science students, a teacher would be well advised to understand that not all students can conduct these forms of inquiry without experiencing various levels of inquiry.

Levels of Inquiry Model of Science Teaching

The Levels of Inquiry Model of Science Teaching (Wenning, 2005, 2010, 2011) provides a framework for inquiry-oriented instruction in the introductory science classroom. It is summarized very briefly here. The author refers readers to the above articles for detailed information and examples exhibiting the use of this model.

Levels of inquiry is an inquiry spectrum consisting of discovery learning, interactive demonstrations, inquiry lessons, inquiry labs (guided, bounded, and free), and hypothetical inquiry (pure and applied). These are arranged in increasing order of intellectual sophistication with the locus of control shifting from teacher to student. Each level of inquiry is associated with intellectual and scientific process skills. Each of the levels in the inquiry spectrum is associated with a 5-stage Levels of Inquiry Model for Science Teaching learning cycle consisting of student-centered activities: observation, manipulation, generalization, verification, and application. Instructional plans based on the inquiry spectrum are known as learning sequences, numerous examples of which are provided by Wenning & Khan (2011).

Conclusion

Science teachers cannot teach what they do not know. This is true both in relation to the content and processes of science. Inquiry is among the most essential of components in the "tool kit" of science teachers. Without a deep understanding of inquiry, its types and approaches, teachers are left handicapped when it comes to teaching using reformed approaches called for in the current science education reform movement. Without an understanding of inquiry and methods for teaching using inquiry-oriented approaches, it is highly unlikely that many, if not most, students enrolled in introductory physics courses will have much of a chance to become scientifically literate in this critically important area.

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References:

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

American Association of Physics Teachers. (1998). Goals of the Introductory Physics Laboratory. *American Journal of Physics, 66*(6), 483-485.

Anderson, F. H. (1985). *The New Organon.* New York: Macmillan.

Costenson, K. & Lawson, A. E. (1986). Why isn't inquiry used in more classrooms? *American Biology Teacher, 48*(3), 150-158.

Hatton, J. & Plouffe, P. B. (1997). *Science and Its Ways of Knowing.* Upper Saddle River, NJ. Prentice Hall.

National Research Council. (1996). *National Science Education Standards.* Washington, DC: National Academy Press.

National Research Council. (1996). *National Science Education Standards.* Washington, DC: National Research Council. National Science Teachers Association (2003). *NSTA Standards for Science Teacher Preparation.* Washington, DC: Author.

National Research Council, (2000). *Inquiry and the National Science Education Standards.* Washington, DC: National Academy Press.

National Science Teachers Association (2004). Position statement on scientific inquiry. Downloaded 8/1/2011 from http://www.nsta.org/about/positions/inquiry.aspx

Rankin, L. (2000). *Lessons learned: Addressing common misconceptions about inquiry, in Foundations,* Vol. 2, Inquiry Thoughts, Views, and Strategies for the K-5 Classroom, Washington, DC: Division of Elementary, Secondary, and Informal Education Directorate for Education and Human Resources, National Science Foundation.

Reif, M. (2008). Dealing with resistance to reform. *The Physics Teacher, 46*(6), 381-382.

Wenning, C. J. (2005). Whiteboarding and Socratic dialogues: Questions and answers. *Journal of Physics Teacher Education Online, 3*(1), September 2005, pp. 3-10.

Wenning, C. J. (2006). A framework for teaching the nature of science. *Journal of Physics Teacher Education Online, 3(3), March, pp. 3-10.*

Wenning, C. J. (2010). Levels of inquiry: Using inquiry spectrum learning sequences to teach science. *Journal of Physics Teacher Education Online, 5(*4), Summer 2010, pp. 11-19.

Wenning, C. J. (2011). The Levels of Inquiry Model of Science Teaching. *Journal of Physics Teacher Education Online. 6*(2), Summer, pp. 2-9.

Wenning, C. J., Holbrook, T. W. and Stankevitz, J. (2006). Engaging students in conducting Socratic dialogues: Suggestions for science teachers. *Journal of Physics Teacher Education Online, 4*(1), Autumn, pp. 10-13.

Wenning, C. J. & Khan, M. A. (2011). Sample learning sequences based on the Levels of Inquiry Model of Science Teaching. *Journal of Physics Teacher Education Online. 6*(2), Summer, pp. 17-30.

Wood, T. (1998). Alternative patterns of communication in mathematics classes: Funneling or focusing? In *Language and Communication in the Mathematics Classroom,* edited by Heinz Steinbring, Maria G. Bartolini Bussi, and Anna Sierpinska, Reston, VA: NCTM, 167-78.

