CHAPTER 2

Best Practice

> “Good teachers of science create environments in which they and their students work together as active learners. They have continually expanding theoretical and practical knowledge about science, learning and science teaching.”
>
> NSES, p. 4

BEST PRACTICE

Research and Teacher Practice

A body of specialized knowledge on which to base practice is one distinguishing characteristic of a professional. A research-based rationale for instructional practice is imperative if we are to counter the popular, but mistaken notion that teaching requires no specialized knowledge (Clough, 1992). It is only recently that the education profession has become more research-based and used research to inform and support teacher practice.

Shulman (1986), as a result of a study of teaching at Stanford University, noted that knowledgeable and skilled teachers possess and use a comprehensive and synthetic kind of professional knowledge in their effort to help students understand complex ideas. He labeled this knowledge as "pedagogical content knowledge" (PCK). PCK includes the special understandings and abilities of skilled teachers that integrate their knowledge of science content, curriculum, learning, teaching, and students. Teachers use this knowledge to make effective decisions about learning objectives, teaching strategies, assessment tasks and curriculum materials (NSES, p. 62).

"PCK differentiates expert teachers in a subject area from subject area experts."

Cochran, 1992

Teachers use PCK as they 'transform' subject matter knowledge for the purposes of teaching and learning. This transformation occurs, according to Cochran (1992), "as the teacher critically reflects on and interprets the subject matter; finds multiple ways to represent the information as analogies, metaphors, examples, problems, demonstrations, and/or classroom activities; adapts the material to students' developmental levels and abilities, gender, prior knowledge, and misconceptions; and finally tailors the material to those specific individuals or groups of students to whom the information will be taught."

Johnson (1990) summarizes the essence of PCK as follows: knowing one's subject; knowing one's audience; and knowing how to introduce one to the other. The important third dimension of this includes organizing the material for the audience and productively involving the audience with the subject matter.

Shulman (1987) provides an overall summary of PCK that would make a nice bumper sticker: "Those who can, do. Those who understand, teach."

Until recently, research into educational practice has been the province of college and university researchers. However, classroom teachers are beginning to play a much more active role in research rooted in daily practice. Through active research into their practice, teachers make instruction the focus of study and analysis. Standards-based reform requires this kind of research because decision making about instruction is so much more complex than in traditional classroom practice. Miller (1988) reports that when teachers conduct research into their practice, they "learn to work with other teachers in groups, to recognize their own expertise and that of their peers, and to challenge the notions that being a teacher is somehow short of being a professional and that teaching is less than a profession."

Developing a professional culture and improving the practice of teaching is important to all teachers. Michael Clough (1992), a science teacher in Eau Claire, WI, notes that a research-based rationale is essential for facilitating "excellence in science instruction for students." Clough uses research for decision making in all parts of his practice, including curriculum development, grant writing, personal evaluation, committee work, parent's night, and when working with student teachers.

Inquiry undertaken by teachers into their practice is referred to by terms such as action research or reflective practice. Many teachers already study what they are doing. Action research and reflective practice add the researcher's criterion: discipline, the development and use of a plan, and documentation. The result is that decisions about instruction are based on and supported by data.

Sparks-Langer and Colton (1991), Calhoun (1994), and Willis (1995) provide suggestions for prospective action researchers.

The information in this chapter is intended not to dictate but rather broaden instructional practice. It describes some of the research on which dimensions of pedagogical content knowledge are based and implications for instruction. It also provides some jumping off points for looking critically at teacher practice. It is hoped that it will inspire teachers to conduct research in their classrooms, to take evidence into account in instructional decision making and to take responsibility for building the profession of teaching science.

The topics cover a wide range of practices in science education and are arranged alphabetically. Each topic includes a brief background, highlights of what research says, implications for classroom practice and references. This chapter does not cover all best practices nor does it cover them in the depth or breadth of a thorough review, as is found in Gabel's handbook of research on science education (1994).

Three resources that can be used for more information are listed at the end of each topic discussed. These are followed by additional references. The list of complete citations is at the end of the chapter. References were chosen with an eye to accessibility as well as to providing rich and productive leads into a growing and complex research literature.

More than one commentator on the conduct and use of educational research has noted that there is a line between reliable research and what is referred to in this age of electronic networks as POV (point-of-view) or educational ideology (cf. Grossen 1996; Hirsch, Jr. 1996 and Pogrow 1996). An effort has been made to focus on practices that are supported by reliable research. Still, consumers of educational research must adopt a stance of inquiry—and this is consistent with the intent and spirit of the *NSES*, the *Minnesota K-12 Science Framework* and the *Minnesota Graduation Standards*. *Caveat Emptor!*

References

Baines 1997; Calhoun, 1994; Clough 1992; Cochran 1992; Cochran, 1993; Grossen 1996; Hirsch, Jr., 1996; Miller, 1988, 1996: Pogrow 1996; Shulman 1986,1987; Sparks-Langer & Colton, 1991; Willis, 1995.

Chapter 2

Active Science

Background

When the National Science Foundation was established in 1950, it ushered in what has become known as the Golden Age of Science Education. During the period from 1954-1974, due largely to the impetus provided by the successful launch by the Russians of Sputnik in 1957, which became the symbol for a crisis in American science education, a new generation of science curricula was developed. With acronyms such as ESS, SCIS, BSCS, ECSP, and SAPA, these new materials were often referred to collectively as the "alphabet soup curricula." What they emphasized, to a greater or lesser extent and with varying degrees of success, was science education that is known as "active science."

"Dewey recognized that learning was an active process. He saw learning as the active engagement of the learner with her surroundings, not the process of an individual mind absorbing knowledge that exists independently. Activity was the word he used to reject this dualistic idea of the separation of the subject and object of learning."

Hein & Price, 1994

According to Shymansky, Kyle & Alport (1982), the pre-1955 science education curricula "emphasized knowledge of scientific facts, laws, theories, and applications; and used laboratory activities as verification, exercises or secondary applications of concepts previously covered in class." The post-1955 materials, on the other hand, "emphasized the nature, structure, and processes of science; integrated laboratory activities into course discussions; and emphasized higher cognitive skills and an appreciation and understanding of the nature of science." The former is often characterized by the phrase "direct instruction" and the latter by the phrase "discovery oriented instruction."

Direct instruction formats emphasize information. Students may feel like outsiders looking in, and believe that scientific discovery is something that others do. One result is that students often find school science irrelevant. Discovery oriented instruction formats emphasize student activity in the classroom. While time consuming, students can learn how to solve problems in science, gain experience in learning to reason scientifically, and learn important science content.

The current reform agenda for science education makes clear that "active science" remains an elusive goal. The kind of science education that children should experience is still described in this reform as "something students do, not something that is done to them."

What Research Says

A justification for active science is found in the widely quoted ancient Chinese proverb: "I hear …and I forget. I see…and I remember. I do…and I understand." While this has an obvious, intuitive appeal, research demands a more critical stance. Some major findings follow:

- Active science has two dimensions, but one has been overemphasized. In addition to doing inquiry and using inquiry procedures—what scientists do in laboratory and field—students must also be involved in what scientists do in their respective research communities: individual and collective sense making.
- It is not enough to do hands-on science. Students must use their scientific knowledge as well as connect that knowledge with what they already know.
- All activities are not equally worthwhile. Although there may be times when they are appropriate, activities on the recipe end of the continuum have limited use, such as learning about and mastering a technique to be used in an investigation. Activities that begin with a question and require students to participate in finding their answer are at the opposite end and are more likely to stimulate and require higher level thinking.
- While students often find activity science (the science processes) fun, mere activity alone can lead students to neither value nor feel comfortable with doing science. In the absence of the analysis of data and the use of tables, histograms, and graphs to draw tentative understandings and to make sense of the work, Rosalind Driver (1987) has said that the "I do and understand" part of the slo-

gan cited above may be better stated as "I do and I am even more confused".

- The science reforms of the 1960s that were most successful emphasized both hands-on inquiry and opportunities for students to talk about what they were learning, beliefs about science, and their difficulties in understanding science.

Implications for the Classroom

- Characteristics of good teaching materials for active science include worthwhile knowledge (e.g., the content in the National Science Education Standards) and activities that support good science education practice, i.e., they meaningfully engage both students' hands and minds. Will the use of the materials lead to a deeper understanding of the natural world? Do the materials require students to develop evidence-based explanations for how things happen?
- Adequate time must be spent on engaging students in activities, identifying a limited number of important terms, explaining and clarifying, and discussing the activity and results as well as helping students make sense of their experience. Active science programs require helping students connect their activities to what they know and to their past experiences.
- While correct answers are always important, good questions, good reasoning, and good arguments are equally important. This means that students should be allowed, indeed encouraged, to argue, ask questions, and disagree but with an emphasis on reasoning and data.
- Science is an enormous enterprise and teaching even a part of it is a process in thoughtful decision-making. What is important for students in my class to know, now? What can and should wait until later? What can they understand? What can be personally investigated by students rather than through media resources? What science materials and processes must students use in their investigations? Such a curriculum is unlikely to include molecular structure or how the solar system works in elementary school.
- The learning environment should be consonant with the culture of science—involvement in doing science; ideas subject to what scientists refer to as "peer review, " i.e., critical and thoughtful evaluation by the class; an emphasis on sense-making within the limitations of what is known and the data available; and reasoning based on evidence.
- Active science implies active assessment; in other words, it must also include the use of a variety of performance-based assessments as well as standard, traditional, multiple-choice tests. Students should be assessed on their inquiry skills as well as on full-fledged inquiries. The assessments should mirror real-life skills and knowledge, represent ideal instructional practice, document what students know and can do, and provide information about the quality of the instructional practice.

Three For Starters

Lowery, L. F. (Ed.) (1997). *NSTA pathways to the science standards: Guidelines for moving the vision into practice. Elementary School Edition.* Washington, DC: National Science Teachers Association.

Texley, J., & Wild, A. (Eds.) (1996). *NSTA pathways to the science standards: Guidelines for moving the vision into practice. High School Edition.* Washington, DC: National Science Teachers Association.

Hein, G.E. & Price, S. (1994). *Active assessment for active teaching*. Portsmouth, NH: Heinemann.

For Further Study

Anderson 1992; Arons 1984; Driver 1987; Finley 1983; NRC 1995; Padilla 1980; Roth, K. J. 1984, 1989, 1992; Project 2061, 1993; Shymansky, Kyle & Alport 1982; Smith & Anderson 1984.

Assessment

Background

Assessment, evaluation, and testing are often thought of as synonyms. They are not. Assessment is the process of gathering information on what students know and can do. Once these data have been collected, the diverse pieces of information are interpreted and integrated into a summary judgment. This is evaluation.

Tests are measuring devices that are used to document student learning on narrowly defined questions and tasks. They are intended to produce a score in a more-or-less neutral and decontextualized environment. Tests are one tool of the assessment process; the tendency in the past has been to reduce assessment to testing, often using the data from a single test to indicate a student's capabilities.

Recently, there has been growing interest in more direct measures of evaluating performance than are found in traditional tests. The result has been a blurring of the boundary between assessment and learning.

Because assessment is a feedback mechanism, it communicates what is important for students to know and be able to do. Assessments should reflect this. If scientific inquiry is important, a student's ability to do scientific inquiry should be assessed in a way that enables them to show what they have learned. On the other hand, when a student's knowledge of specific and important facts is required, a multiple-choice test may be appropriate. Assessments must reflect what we really want students to know and be able to do.

> *"In the vision described by the Standards, assessments are the primary feedback mechanism in the science education system. They provide students with feedback on how well they are meeting expectations, teachers with feedback on how well their students are learning, school districts with feedback on the effectiveness of their teachers and programs, and policy makers with feedback on how well policies are working. This feedback in turn stimulates changes in policy, guides the professional development of teachers, and encourages students to improve their understanding of science."*
>
> NRC, 1996

What Research Says

- Performance assessments, including hands-on performance of complex tasks in real time, can be reliably scored.
- Different aspects of achievement are measured by traditional tests and performance measures.
- The development of alternative assessments is time consuming and expensive.
- There are few differences between boys and girls on performance measures. This is in sharp contrast to gender differences on paper-and-pencil tests.
- Students do not necessarily do better on performance tests than on other tests; they perform differently because the tasks are different.
- There is a wide gap between the ability of students to demonstrate procedures and their ability to explain the procedures.
- Exchangeability is the extent to which two or more measurement methods provide the same information about a student's achievement. Performance tests are not equally exchangeable. Each method appears to measure different yet related aspects of science achievement.
- A number of meaningful tasks are required to increase the dependability of a generalization about student performance and/or program effectiveness.
- Questions of fairness/equity are as important in performance assessments as in other forms of assessment. Wording, topic or task selection, format, and scoring approaches can all influence performance, as can "consequences" and environment.
- A variety of assessment formats is required to obtain a comprehensive view of student achievement, particularly for learning disabled and low achieving students.
- Higher order or lower order thinking can be tested by both multiple-choice and performance items.

Implications for the Classroom

- The range of alternative assessment possibilities is limited only by human imagination. They include performance, observations, interviews, conferences, questions, concept maps, student self-assessments, journals, pencil-and-paper alternatives such as explaining a choice, pre/post unit assessments, embedded assessments, visual diagrams, computer simulations, drawings, projects, investigations, inquiries, posters, design projects, writing, and portfolios.
- Mathematics educator Jean Stenmark offers two important pieces of advice to educators about making changes in classroom assessment practice:

  1. *Don't try to do it all at once*. Start small but start somewhere.

  2. *Don't try to do it all alone.* Find someone to work with, preferably at your grade level or within your discipline.
- The process of developing assessments is messy, time-consuming, sometimes frustrating, and requires much effort. It must be understood from the outset that this is an iterative process. Learning activities are excellent sources of assessment ideas and our professional journals and books are beginning to include examples and descriptions of teacher's experiences.
- Identifying the "big idea" or central learning of a unit is important and it is often not as transparent as it first appears. It's the "What is worth knowing?" question.
- Once a central learning has been identified, criteria for judging student learning should be developed. Checklists are a useful way of displaying criteria. This is the evidence question. If you are developing an assessment for graphing or tables, checklists will help you clearly identify the characteristics of a good product. There is often confusion between rubrics and checklists. Rubrics tend to be less specific than checklists. They are quality descriptors on a continuum from poor to excellent that are more likely to be useful to both teacher and students after they have experience using checklists.
- There are reasons to work with a colleague as assessments are developed. One is support. Another is to examine and discuss student responses to assessments. Some authors recommend that the use of student responses should precede the development of evaluation criteria. This sequence is up to the teacher. But do not throw student work away. Use it. Sit down with a colleague and separately place the student responses in piles, e.g., poor and excellent or poor, medium, and excellent. Then, use them as a basis for discussion about the assessment. This will help to revise and sharpen checklists, provide insights on what is meant by quality work and convince others that all of this can be reliably done.
- One of the uses of alternative assessments is to inform and help make decisions about instruction. What needs to be emphasized, de-emphasized and/or done differently? Eventually, you will face the issue of scoring alternative assessments and grading them. This is the "How do we describe quality work?" question. You can assign points to a checklist against a standard although assigning points is not necessarily straightforward. Students should have access to the checklists as they perform. They can also make a judgment about the quality of their work and this can be used as the basis for a discussion with them about their progress.

There is a variety of advice on developing alternative assessments. This is to be expected in a field as young as alternative assessment. The large, but exciting task is to become a more informed consumer of assessments.

Three For Starters

Hart, D. (1994). *Authentic assessment: A handbook for educators*. Menlo Park, CA: Addison-Wesley.

Hein, G. E., & Price, S. (1994). *Active assessment for active science: A guide to alternative assessment*. Portsmouth, NH: Heinemann.

Jorgensen, M. (1994). *Assessing habits of mind: Performance-based assessment in science and mathematics*. Columbus, OH: ERIC Clearinghouse for Science, Mathematics, and Environmental Education, The Ohio State University.

For Further Study

Baxter & Shavelson 1994; Doran 1990a, 1990b; Harnisch 1994; Herman, Aschbacher & Winters 1992; Moje & Handy 1995; Science & Children 1994; Science Scope 1992; Shavelson & Baxter 1992; Stenmark 1991; Wiggins 1989a, 1993; Worthen 1993.

Brain Research

Background

Educators are hearing a lot about the brain lately. Developments in molecular biology, behavioral studies, endocrinology, and imaging technology have allowed researchers to literally see what is happening inside the brain while it works. This research, coupled with developments in cognitive psychology, has resulted in a growing interest in what is referred to as brain-based learning which, of course, is a classic oxymoron. In humans, all learning is brain-based but, as Renate Caine notes, this phrase is a way of pointing out and emphasizing that there should be a relationship between what we know about how the brain works and how children can learn best. The purpose is to put research into practice.

It was only a few years ago that the brain was thought of as a static organ. Three pounds of walnut shaped matter housing approximately 100 billion neurons that are connected in specific and intricate ways. The brain was viewed as rule-bound and hard-wired, preset and fixed by a biological blueprint which, more-or-less like a tape-recorder, stored whatever it heard or saw or tasted or felt. However, in the past decade or so, research has shown that, although the basic structural features of the brain are determined by genes, it is the environment that provides the necessary stimulation for the brain to achieve its potential. Nature and nurture must work together in tandem.

> *"(Descartes) did not realize the human brain was the most complex structure in the known universe, complex enough to coordinate the fingers of a concert pianist or to create a three-dimensional landscape from light that falls on a two-dimensional retina. He did not know that the machinery of the brain is constructed and maintained jointly by genes and by experience. And he certainly did not know that the current version is the result of millions of years of evolution. It is difficult to understand the brain because, unlike a computer, it was not build with specific purposes or principles of design in mind. Natural selection, the engine of evolution, is responsible."*
>
> Fischbach, 1992

What Research Says

- At birth the human brain has all the neurons it will ever have.
- The brain is not only shaped by the outside world but uses the outside world to shape itself. Most of the circuitry develops throughout life as a result of a person's experiences.
- The brain goes through four major periods of restructuring: fetal development, birth to one year, four years old to age ten, and thereafter. During these periods brain cells must have certain kinds of stimulation to develop the things the brain can do, such as vision, language, and reasoning.
- Nerve connections can be modified throughout life and new connections can form even late in life.
- Brain cells are interchangeable during early development, i.e., brain cells that interpret sound can be converted into cells that can process visual images from the eyes.
- Aggression, violence, and crime appear to be rooted in the brain's biological reactions to violent and stressful experiences.
- The brain is the ultimate, hard-working athlete. The harder it exercises, or is used, the more in shape it appears to be as measured by the number of connections found. It is, in the words of reporter Ronald Kotulak of The Chicago Tribune, the "ultimate use-it-or-lose-it machine."
- Nerve connections (synapses) that are not strengthened by continuing stimulation from the environment die off.
- The left side of the brain processes information faster than the right side of the brain.
- Babies listen to speech. While it may appear that infants are oblivious to human words, the vocabulary they hear makes an impression on their brains. Television is not a substitute for this language.
- All fetuses begin as females. When the male sex hormone, testosterone, is released, not only do male features develop, but the hormone literally shapes the brain. The cognitive variations between the sexes in the way in which they solve intellectual problems reflect differing hormonal influences on brain development.

- Developmental experiences determine the ability of the brain to do certain things.
- Cognitive patterns in both men and women due to hormonal influences may fluctuate throughout life.

In the Classroom

- Content should be presented using a variety of multifaceted teaching strategies: individualistic, groups, physical activity, artistic variations, and musical interpretations. Students should have opportunities to express their auditory, visual, tactile, and emotional preferences as well as participate in these experiences. These various forms of representation influence our use of the processes, the way we think, and our understanding.
- Learners should be encouraged to explore, gather, and use information.
- The brain is a pattern seeker and pattern maker. Learning experiences should be designed to help learners identify patterns which facilitate connection with, as well as the modification of, previously learned patterns. Because we are so adept at seeking patterns we can also be deceived by them, and therefore work in science should emphasize the use of data, evidence, and reasoning.
- The use of books is important in learning but, as Larry Lowery points out, "books can only do this if our experiential foundation is well prepared. … To learn about electricity, we must explore relationships among batteries, wires, and bulbs."
- There are significant differences between young learners and scientists in the nature and quality of their understanding about the world. As students develop, they pass through various abilities and ways of thinking about the world. These represent different ways of organizing the experiences of school learning, each providing a different view of the world. Understanding grows and cognitive development plays an important role in it. Students should have many opportunities to explore the natural world and think about it within their various stages of intellectual development.
- The brain requires external stimulation. This means that the curriculum is designed to change minds—Elliot Eisner refers to the curriculum as a "mind-altering device"—therefore, it should be chosen with care and should emphasize the important content and processes of the discipline being studied.
- The brain connects emotion and cognition, therefore the classroom environment should be one that instills learners with confidence and is not threatening. Work should be appropriately challenging and should teach students that they are not helpless; they have some control over learning and are expected to exert that control.

Three For Starters

Caine, R. N., & Caine, G. (1991). *Making connections: Teaching and the human brain*. Alexandria, VA: Association for Supervision and Curriculum Development.

Caine, R. N., & Caine, G. (1990, October). "Understanding a brain-based approach to learning and teaching." *Educational Leadership,* pp. 66-70.

Sylwester, R. (1995). *A celebration of neurons: An educators guide to the human brain*. Alexandria, VA: Association for Supervision and Curriculum Development.

For Further Study

Abbot 1997; Brandt 1997; Caine 1990, 1995; Caine & Caine 1997; Calvin 1996; Cohen 1995; Eisner 1997; Fishbach 1992; Kotulak 1996; Lawson 1994; Lowery 1990; Pool 1997; Scientific American 1992; Wills 1993.

BEST PRACTICE

Constructivism

Background

For most of this century, behaviorism, a theory about how humans learn, has driven educational practice. It is a well-entrenched model of learning, indeed most of us are products of such educational systems. Behaviorism assumes that students are a blank slate (*tabula rasa*) on which the knowledge of others is simply written. Behaviorism is characterized by atomized behavioral objectives, tightly sequenced curricula, drill and practice, and an overwhelming emphasis on the transmission of facts and principles. It assumes that through mastering series of simple steps, students are then able to engage in higher order thinking.

> *"...at present, the constructivist model is descriptive, not prescriptive. ... It is important to understand at the outset that constructivism is not an instructional approach; it is a theory about how learners come to know."*
>
> Airasian & Walsh, 1997

Research on how students make sense of science and mathematics has led to new ideas about learning. It is difficult to locate the birth of a new idea but certainly since the mid-1970s, research in cognitive psychology opened a fruitful lead known as constructivism. Constructivism, like a prairie grass, is deeply rooted in a number of research and intellectual traditions. Most familiar to educators is the work in this century of Jean Piaget. Historically, constructivism has been traced to the Neapolitan philosopher Giambattista Vico (1710) to whom we owe the modernized, widely-cited slogan, "To know means to know how to make." Constructivism has been referred to by one science educator as "the most exciting idea of the past 50 years."

What Research Says

- Humans are meaning-makers. People learn by actively constructing and reconstructing their own knowledge about how the world works. It is not passively received from learning environments.
- Learning involves an interplay between what we know or believe about something and new knowledge. Humans learn by modifying old ideas, not simply by accumulating new ones. New information is weighed, thought about, compared, and may be reconstructed into new, deeper and more connected understanding. This process is a continuing one. It is also one of the reasons that learning does not always feel good. After all, it regularly challenges our beliefs, and the subsequent construction-reconstruction often includes periods of feeling perplexed, frustrated, and sometimes even angry.
- New meanings are both personally *and* socially constructed or negotiated. Our social worlds influence the way we make sense of the natural world. In science and mathematics, as well as in science and mathematics classes, the meaning of concepts are socially negotiated.
- While we can explain things to others, we cannot understand it for them. One overwhelming reason for helping children construct meaning is that science is a human creation. Having students do science can help them see that science is something that people, who are just like them, do.
- Students construct meaning; it happens whether we like it or not. As Lederman and Niess (1996) note, "regardless of instructional approach, the opportunity to construct one's understanding is always…present."

Implications for the Classroom

- When learning is viewed as a continuing process of construction-reconstruction, the content and tasks must be of the kind that requires an ongoing pattern of organization and reorganization. This means teaching to and with the big ideas of science clearly in mind. Curricula must deal directly with a few important ideas that are progressively sequenced.
- It is clear that we cannot teach everything of importance. Constructivism lends considerable support to the contemporary slogan that "Less is More," the assertion that it is better to learn fewer

things better than a lot of things poorly. Humans do not discard closely held ideas easily. The construction of new knowledge takes time and sufficient experiences in new contexts. This argues for a focused, coherent curriculum.

- A central tenet of constructivism is to create autonomous learners. Students who come to know science and mathematics as a way of knowing and doing are more likely to be able to know how to transform their own questions into systematic learning and to know the pleasure that follows in constructing knowledge that is new to them. Classrooms must promote the ability to ask and sustain this kind of questioning and learning.
- To make sense of the environment, individuals actively interact with it. Students must be actively engaged in learning. Learning must be "hands-on/minds-on."
- Because learning is a social process, it involves a constant checking against personal experience and negotiation with peers and teachers. Because learning depends on what we know and believe as well as the classroom environment, both must be acknowledged and taken into account in the classroom. Constructing meaning is an active process that includes hands-on learning with the objects and materials of science *and* a focus on interpretation and explanation of student findings. What was once referred to as discussion must now become a classroom conversation among colleagues. Students must have opportunities to explicitly express their ideas which makes them available for scrutiny, reflection, and for change. At the same time, these ideas must be respected and used by all as grist for learning.
- Science has agreed upon understandings about how the world works. Many of these understandings are, of course, tentative and subject to change in light of new evidence. Constructivist classrooms are not places where all ideas about science are equal or where students vote on ideas and explanations. Constructivism requires teachers to intervene, not by saying to a student, "that's wrong," but through questions, activities, demonstrations, or requiring that investigations are repeated when the data are ambiguous. The idea is to help students reconsider their ideas as they develop and refine understanding.
- Hands-on learning is a must in science classrooms. In Catherine Fosnot's (1991) words, "the learner must have experience with hypothesizing and predicting, manipulating objects, posing questions, researching answers, imagining, investigating and inventing."

Three For Starters

Clements, D. H. & Battista, M. T. (1990, September). "Constructivist teaching and learning." *The Arithmetic Teacher*, pp. 34-35.

Watson, B. & Konicek, R. (1990). "Teaching for conceptual change: Confronting children's experience." *Phi Delta Kappan*, May: 680-685.

Yager, R. E. (1991). "The constructivist learning model." *The Science Teacher*, September:52-57.

For Further Study

Airasian & Walsch 1997; Anderson 1991; Brooks & Brooks 1993; Fosnot 1991; von Glasersfeld 1989; Good, Wandersee, & St. Julien 1993; Lederman & Niess 1996; Piaget 1948, 1954; Tobin 1993; Vico 1858; Wiggins 1989b; Zahourik 1997.

Developmental Considerations

Background

For more than sixty years, the Swiss psychologist Jean Piaget studied how children construct their knowledge of the physical world or what he termed as genetic epistemology (genetic = developmental and epistemology = the study of knowledge). Piaget's interests in biology and education (his doctorate was on mollusks) is evident in his work although it must be emphasized that he used terms, like adaptation or organization, metaphorically, not as explanations for human development.

"It is now clear that we have tended both to underestimate children's competence as thinkers and to overestimate their understanding of language."

Donaldson, 1979

Piaget's theory of cognitive development includes four distinct patterns of intelligent action: the sensorimotor stage, the preoperational stage, the concrete operational stage, and the formal operational stage. This sequence is invariantly ordered. Bybee and Sund (1982) refer to these stages, respectively, as the active child, the intuitive student, the practical student, and the reflective student.

Although learning begins before birth, the sensorimotor period is from birth to 2 years. It encompasses a transition from sense and motor functions to intellectual and psychological behaviors and the gradual inclusion of others and the environment. Between the ages of 2 and 7, known as the preoperational period, children internalize physical actions as mental representations. From ages 7 to 11 or 12, children's thought is limited to encounters through direct experience and is referred to as concrete operational. During the period of formal operations, roughly from the age of 11 or 12 to 14 or 15 years, reasoning strategies become systematic and children can think in terms of abstractions. This period is characterized by great variability in thinking abilities and children demonstrate both concrete and formal reasoning patterns.

It is recognized as one of Piaget's central insights that we learn through repeated conceptual reorganization; our intellectual development is one of progressive adaptation as concepts and the physical environment interact. As we learn, concepts are modified and/or are woven into an ever richer web of conceptual connections.

What Research Says

Although Piaget was not interested in teaching and had little to say about education, his theory on the genesis of knowledge and, in particular, the distinctions between concrete and formal operational thought has proved very useful to educators. The research literature on Piagetian theory, pro and con, is much too vast to summarize either quickly or easily, perhaps even to completely know. These are the highlights of a few of the findings which have implications for educators.

- Human understanding of concepts occurs gradually rather than suddenly. It is individuals that make meaning, although social interaction plays a part in promoting cognitive development. Context is both a subtle and an important factor in learning. Learning involves conceptual change, but the new situation must be both somewhat familiar and somewhat strange. Development is spurred by the encountering and constructive handling of conflict; its acceleration, known as "the American question," can occur only to a limited degree. Activity, as in active learning, includes both physical and mental activity.
- Stage theory can be misapplied; it is not a neat, limiting pigeon-hole where age equals stage but rather a useful way of classifying and ordering the development of intelligence. To classify a student is a mistake. Individuals tend to exhibit the same kind of ideas as other individuals within two to three year ranges which are replaced as they grow older. There is disagreement about the placement of specific abilities in the Piagetian developmental sequence.

Implications for the Classroom

- While science educators have applied Piagetian theory extensively for at least the last 35 years, profound and difficult questions about the developmental appropriateness of content and process are still a source of disagreement among educators. The Minnesota K-12 Science Framework provides an informed lens on what is within reach of learners at particular grade levels.
- Constance Kamii (1984) noted that Piaget once "stated that a school based on his theory would be radically different…." How? What would it look like? According to Kamii, Piaget's most important ideas are intellectual and moral autonomy and constructivism. For Piaget, autonomy—being governed by oneself—is more likely to be developed when adults "exchange points of view with children." This includes having students explain their reasoning, taking a stand and confronting opposing opinions and/or interpretations, and negotiating meaning. The kind of conversation that is implied by the above can only occur when all ideas, including wrong ones, are used and respected and when classrooms emphasize the kind of persuasion a scientist uses when presenting the results of her research. What is the meaning of experimental and discrepant experimental results? What if…? How would you design and perform a confirmatory or disconfirmatory test?
- Metaphorically and in practice, the Piagetian classroom is a construction zone (Roth, W-M. 1993) where students are involved actively and collaboratively, using materials and minds, in the construction of knowledge. It is important that students work and talk with other students. This can help expose concepts for discussion and facilitates the construction of both new conceptual knowledge and procedural knowledge.
- Piaget developed an interviewing technique known as the "clinical method." Since Piaget's original work, interviewing techniques have not only become more widely used, they have also evolved into a more rigid system for learning how individuals grasp concepts. Interviews are also one of the many methods recommended and used in alternative assessment. While time consuming, they are revealing. Questioning students in a one-to-one situation can help us realize how hard it is to understand as well as to be understood, probe a student's understanding— what they know and how they came to know it—provide another option for a student to tell what s/he knows, and to examine the depth of ideas that students hold (and sometimes they even reveal our own misconceptions about science as well as teaching and learning!). Interviews require excellent knowledge of the subject matter and practice. They are worth trying. You can start by developing some questions that you think will assess deep understanding of a science concept. Often such interviews are facilitated through the use of physical materials and equipment with students but with regard to limiting them to the essentials.

Three For Starters

Kamii, C. (1984, February). "Autonomy: The aim of education envisioned by Piaget." *Phi Delta Kappan*, pp. 410-415.

Lowery, L. F. (Ed.) (1997). *NSTA pathways to the science standards: Guidelines for moving the vision into practice. Elementary School Edition*. Washington, DC: National Science Teachers Association.

Texley, J., & Wild, A. (Eds.) (1996). *NSTA pathways to the science standards: Guidelines for moving the vision into practice. High School Edition*. Washington, DC: National Science Teachers Association.

For Further Study

Bybee & Sund 1982; Donaldson 1979; Gardner 1991a; Inhelder & Piaget 1958; Lentz & Coe 1984; Lowery 1990; Metz 1995; Piaget 1957, 1962, 1970a, 1970b, 1970c, 1973a, 1973b, 1975; Roth, W-M 1993; Siegal 1991; Subbotsky 1993.

Group Learning

Background

"Definitions notwithstanding, I am convinced, with many others, that learning is enormously enhanced when it becomes a shared enterprise with others."

Applegate, 1995

Group learning has a long history in U. S. education and has always been a part of skillful teachers' repertoire. However, recent interest, research, and practice stems from the work on cooperative learning in the late 1940s by psychologist Morton Deutsch (1962), Columbia University. Deutsch proposed three possible motivational goal structures for students: competitive, individualistic, and cooperative.

In competitive classrooms, students compete with one another to see who is best; there are clear winners and losers. In classrooms that promote individualistic interactions, students work independently and the achievement of other students is irrelevant. In cooperative learning situations, student achievement is interdependent and individual students can achieve their learning goals only if other students achieve their goals.

Cooperative learning encompasses a set of alternatives to traditional classroom practice. It may involve dividing a complex task such as a science experiment into parts and having each group member complete one of the parts. This strategy is sometimes referred to as "divide-and-conquer." It may also involve a group of students working together to achieve a pre-determined outcome.

What Research Says

- Academic Achievement. Overall, research and analysis of historical studies, some dating to the 1920s, support the positive effects of cooperative learning on student achievement over a wide range of age groups. However, the details are complex and there is conflicting research.
- Social/Workplace Skills. There is no question that in science, mathematics, and engineering there is a growing need for productive work groups and that collaboration in research is on the rise. Projects are increasingly large and complex and group work is common. Group learning requires the exercise of a variety of skills such as leading, following, supporting, listening, communicating, decision-making, negotiation or bargaining, explaining difficult concepts, working effectively with others, seeking feedback, and constructively resolving conflicts. There are some researchers who appear to believe that these will occur more or less naturally in groups while others strongly note the importance of providing direct instruction in interpersonal and small-group skills. The evidence suggests that groups must be structured carefully to be successful as well as cooperative.
- Self-Esteem. A variety of research has shown that the use of cooperative groups enhances students' self-esteem. Cooperative groups combine the academic and the social dimensions of schooling, both of which are important to students. As students in groups focus their attention on important learning outcomes which they are expected to be able to learn, students experience a different playing field, one on which they are competent colleagues rather than competitors. There is also research which shows that cooperative learning has a positive effect on groups consisting of multi-ethnic, mixed-gender, and mixed-ability students.

- Cooperative groups tend to be structured and students are often assigned roles and tasks, e.g., "materials getter," "manager," "recorder," "reporter," etc. Cooperative groups are useful in teacher-driven activities. Some are recognizing the emergence of a new kind of group, one that is consistent with standards-based education.

In collaborative groups, roles are less structured and are negotiated among participants. As students assume the responsibility for their investigations, they may work not only with classmates and the teacher, but also with other teachers, community members, telecommunications experts and others to answer questions they ask about materials. Students may still profit from "training" but the form is more likely to be on a need or ad hoc basis.

Implications for the Classroom

- According to Johnson & Johnson (1991), the basic components of cooperative learning include:

  Positive interdependence. Students must recognize that they need one another to complete the task, i.e., they can reach their learning goals if and only if all other students in the group reach their learning goals. This is often summarized as "We sink or swim together."

  Face-to-face interaction. Students must be in situations where they help one another to learn and complete the learning task, i.e., they explain, discuss, teach, and make connections between concepts.

  Individual accountability. Groups are designed to help everyone learn but individual students have ultimate responsibility for their own learning. One of the concerns in the use of small groups is the so-called "hitchhiker" problem where certain students do the majority of the work and assessment. Teachers who spend time explaining the reasons for cooperative group work and who do not grade on a curve do not often report the hitchhiker problem.

- Formats for assessment of groups include the use of observations, interviews, individual tests followed by group tests, weekly group tests and individual final exams. Rowe (1973) noted that "science materials make the ways in which students work together visible—and audible." The quality of these interactions with materials and of students with one another can be recorded on checklists to observe how well groups are functioning and how well the science is being learned. Applegate (1995), a zoologist at Rutgers, suggests an interesting use of cooperative learning in graded tests. He first has students take a test individually and turn it in. Then, students reconsider their original responses with their group. Students complete the test a second time as individuals. When the tests are graded, the first sheet is scored and then points are added or subtracted on the second sheet. Over four years, Applegate has subtracted points 2% of the time, added them 80% of the time, and made no changes 18% of the time.

- *Small group, group processing, and interpersonal skills* must be directly taught. These include overt teaching of trust-building (one college chemistry professor takes his organic classes through a low-ropes challenge course!), leadership, communication, conflict management skills, and functioning as a group to achieve learning goals and learn how to work with one another. Linn and Barbules (1993) raise some important questions about the decision to use groups, questions that can be used to guide the use of groups in classrooms. "What is best learned in groups? When will one or another group activity foster knowledge construction? For what additional goals is group learning helpful or detrimental? Who benefits from group learning? And how, in light of these reflections, can group learning be made an effective part of a repertoire of teaching and learning activities?"

- The constructivist ideas on how we learn suggest the value of learning in productive groups, e.g. the focus of attention is on learners, not the instructor. Students experience science as a human endeavor and by discussing their work with others, students gain a better understanding of procedures, data analysis and interpretation and of science concepts.

Three For Starters

Johnson, D. W., & Johnson, R. T. (1989/1990, December/January). "Social skills for successful group work." *Educational Leadership*, pp. 29-33.

Johnson, D. W., Johnson, R. T., & Holubec, E. J. (1986). Circles *of learning: Cooperation in the Classroom*. (Revised). Edina, MN: Interaction Book Company.

Scott, L. U., & Heller, P. (1991, January). "Team work." *The Science Teacher*, pp. 24, 26, 27-28.

For Further Study

Applegate 1995; Deutsch 1962; Johnson & Johnson 1978, 1987, 1989a, 1989b, 1991; Lawrenz & Munch 1994; Linn & Barbules 1993; Marx, Blumenfeld, Krajcik & Soloway, 1997; Ossont 1993; Rowe 1973; Saner, McCaffrey, Stecher, Klein & Bell 1994; Slavin 1983, 1988, 1989/90; Slavin, Madden & Stevens 1989/1990.

History and Nature of Science

"The essence of teaching science as inquiry would be to show some of the conclusions of science in the framework of the way they arise and are tested."

Schwab, 1962

Background

Much of the research on the use of the history of science in science education began in the 1950s and the 1960s and focused on curriculum design. The National Science Foundation (NSF) provided support to Harvard University to develop *Project Physics* which was the first major curriculum to support an integrated historical approach to teaching science. The NSF also supported the development of *Invitations to Inquiry* in biology which made use of the history of science. Recently there has been a call for research on how history can be applied to instruction, learning, and assessment. In addition to having students do science, educators also want them to develop understandings about how science is done. The inclusion of the history of science can contribute to that.

There has been considerable research on students' understanding of the nature of science as well as teachers' conceptions and classroom variables. It is recognized that both students and teachers must have an understanding of the tentativeness of the scientific enterprise. Lederman (1994a) notes "there is no singularly preferred or informed nature of science and that the nature of science is as tentative…as scientific knowledge itself."

What Research Says

- Students who took a science course emphasizing a historical approach (*Project Physics*) found physics more enjoyable and understandable.
- The integration of history in a course (*Project Physics*) greatly expands students' views of scientific inquiry. Rather than believing in the idea of a unitary "scientific method," students learned that science was a variegated process which included diverse approaches and methods.
- The historical approach, as used by students taking *Project Physics*, does not interfere with learning the content of science.
- The language used in presenting scientific concepts must be explained and thoroughly discussed to emphasize the ways scientific explanations are used, the role of humans in the development of scientific knowledge, and usefulness, e.g., models, what they are and what they are not.
- Misconceptions which endure about the enterprise of science include: 1) the hierarchy that hypotheses become theories which become laws; 2) a hypothesis is simply a guess; 3) there is a general and universal scientific method; 4) scientific knowledge is sure and a faithful copy of the world; 5) the methods of science are an avenue to absolute truth; 6) science depends more on procedures than it does on creativity; 7) science can answer all questions; 8) scientists are particularly objective and logical; 9) experiments are the sole route to scientific knowledge; and 10) all work in science is reviewed to keep the scientific process accurate and honest.
- The logical-positivist position that observation provides direct access to reliable knowledge about the world independent of a prior conceptual framework is incorrect.
- The most important factors influencing students' beliefs about the nature of science are the instructional approaches and decisions of the teacher about the activities that students participate in within the context of the curriculum.
- It is not clear whether teacher's understanding of the nature of science is directly related to the development of students' understanding of the nature of science or whether other variables in classroom practice are more important in developing such understanding.

Implications for the Classroom

- Historian of science Stephen Brush suggests three ways history can be used to teach students about the nature of science.

  [1] Many of the major ideas of science deal with broad philosophical questions about our place in the universe. These questions are of great interest to adolescents who are seeking answers to such questions. Many of these issues are generally ignored in textbooks. Such ideas include Newton's "clockwork universe" theory, the age of the earth, evolution, the behavior of sub-atomic particles, and issues of cause and effect. Studying of these kinds of questions provides students insights into how scientists think and use experiments, evidence, and theory as well as the importance of imagination and creativity in science.

  [2] Science is more than facts about the world. Emulating the methods that scientists use to establish the facts of nature can help students understand science as a way of knowing. Such knowledge can help students gain an appreciation for the idea of tentativeness in science and how specific concepts and theories change and why.

  [3] The study of the history of science includes opportunities for noting the contributions of women and minorities, especially if their contributions are integrated with the appropriate standards and concepts.

- When students pursue their own research questions in science, they should be allowed to pursue so-called "blind alleys." These are part of the experience of scientists although they are seldom reported in the literature because of space limitations. These explorations must be fully debriefed to help students realize that they have learned some things even though the results were inconclusive or wrong. Students should carefully analyze, report, and discuss such work with their peers. This will help students construct an understanding of the nature of scientific inquiry.
- Because observation is theory-dependent, the skills of observation have to be learned within a conceptual framework that helps students know what to look for, where to look, how to recognize "it" when they see it, when to accept and reject observations, as well as when to know that more observations are required.
- To assist students in understanding the nature of science, emphasize inquiry-oriented instruction, higher order thinking skills/questioning within a supportive and intellectually risk-free classroom environment.

Three For Starters

Lederman, N. G. (1992a). "Students' and teachers' conceptions of the nature of science: A review of the research." *Journal of Research in Science Teaching*, *29*:331-359.

Lowery, L. F. (Ed.) (1997). *NSTA pathways to the science standards: Guidelines for moving the vision into practice. Elementary School Edition*. Washington, DC: National Science Teachers Association.

Texley, J., & Wild, A. (Eds.) (1996). *NSTA pathways to the science standards: Guidelines for moving the vision into practice. High School Edition*. Washington, DC: National Science Teachers Association.

For Further Study

Brush 1974, 1989; Cushing 1989; Duschl 1994; Lederman 1992b; Lederman & Niess 1997; Matthews 1989; McComas, 1996; Russell 1981; Schwab 1960, 1962, 1965.

The Laboratory

Background

A distinctive feature of science teaching is laboratory work. It has a long history in American education, spanning more than 125 years. During this time, the laboratory has been both promoted and dismissed as an essential component of the science curriculum. The place of laboratory work was raised to new prominence in the major curriculum reforms of the 1960s when laboratory activities were designed to help students solve problems, learn the processes of doing science, and develop understanding of concepts. What is surprising is that so little is known about the role of the laboratory in learning. Hofstein and Lunetta (1982) concluded their review of laboratory work with the interesting observation that the wrong questions have been asked and that many of the studies reported on the role of laboratory work were flawed by poor design.

"Science teaching must take place in a laboratory; about that at least there is no controversy....Both teacher and pupil are united...in a belief that experiments is the right tool."

Solomon, 1980

What Research Says

- Laboratory work can play an important role in the development of logical reasoning in science, higher-order cognitive abilities, inquiry skills, concepts, and positive attitudes toward science.
- Laboratory work provides a wide variety of students with opportunities to be successful in science.
- For meaningful learning and the promotion of conceptual change as a result of laboratory experiences, students must reflect on their findings as well as interact with a wide variety of resources, including their peers, the teacher, and resource materials.
- Students and teachers differ in their view of the importance of laboratory work. For students, learning how to do practical things is important. For teachers, the laboratory provides students with the opportunity to experience science's way of knowing and building understanding of science concepts.
- Students need opportunities to engage directly with the materials of science. Such opportunities for manipulating concrete materials in the laboratory help students grasp and meaningfully learn many of the complex and abstract concepts of science.
- Research on the use of microcomputers in laboratories and calculator-based laboratories (CBL) is limited. Students can benefit from computer simulations *after* experiences with real phenomena, e.g., students who have first made their own graphs pay more attention to details than students who use graphs made by the computer. The quality of conclusions is improved since the amount of time between the experiment and data analysis is reduced. The student has more time to think about the data rather than being mired in the details. The use of probes provides an opportunity to collect data on a variety of potentially related variables. There is some evidence that students may believe that information presented by the computer is accurate, even when there are flaws in the data.
- There is abundant evidence that laboratory experiences per se do not result in the acquisition of laboratory skills.

Implications for the Classroom

- Discussion as a teaching strategy has been widely devalued in laboratory work. Time must be provided for active processing and interpreting laboratory work if concept acquisition and conceptual change are to result. Students' attention must be directed to analysis, interpretation, negotiation of meaning with peers of methods used and their results, and reading materials that extend and clarify meaning.
- The history of science may be used to enrich laboratory work by helping students think about the nature of science. Through it students can integrate theory and practice.
- If the learning potential of laboratories is to be fully realized, careful planning is essential. Key con-

cepts and relationships must be identified.

- The mastery of scientific concepts and inquiry skills require social activities. Active, purposeful cooperative learning in the laboratory can help attain this goal.
- Pencil and paper are not adequate for assessing student performance in the laboratory. Performance assessments must be included in the mix of assessments used in science.
- Some laboratory work should include investigations that make use of so-called "real world" materials and problems, i.e., learning science in context. This might include the chemistry of cooking, amusement park/toy physics, and the biophysics of hearing loss.
- Care should be taken in the selection and teaching of laboratory skills. They should be taught to a level of competence and with an eye to their use in worthwhile activities, e.g., the use of scientific inquiry in the area/discipline being studied.
- Conceptual structures give meaning, purpose and direction to laboratory work and the two must be carefully as well as consciously integrated for learning to result. Explicit instructional efforts must be devoted to them, including the learning of the processes of science.

The Laboratory

TYPE V *Full scientific inquiry*. Students formulate the questions to be investigated and methods of data collection, make interpretations, and draw conclusions.

TYPE IV *Partial scientific inquiry*. Students receive instruction and materials from the teacher, but do not know what results or conclusions to expect. The emphasis is on finding relationships in data and making evidence-based conclusions.

TYPE III *Guided discovery*. Students are presented with a problem and develop their own methods for collecting data. This develops data collecting skills such as measuring, identifying, controlling variables, collecting and recording, and making interpretations.

TYPE II *Verification*. Students verify concepts or principles previously studied. Problems and procedures are specified.

TYPE I *Skills development*. Does not require formal reasoning. Teaches important skills such as measurement and observation, or how to use laboratory and scientific equipment.

Adapted from Ivins, 1983

Three For Starters

Lowery, L. F. (Ed.) (1997). *NSTA pathways to the science standards: Guidelines for moving the vision into practice. Elementary School Edition*. Washington, DC: National Science Teachers Association.

Texley, J., & Wild, A. (Eds.). (1996) *NSTA pathways to the science standards: Guidelines for moving the vision into practice. High School Edition*. Washington, DC: National Science Teachers Association.

Tobin, K. (1990). "Research on science laboratory activities: In pursuit of better questions and answers to improve learning." *School Science and Mathematics*, *90*:403-418.

For Further Study

Bates 1978; Driver 1982; Driver & Bell 1986; Gunstone & Champagne 1990; Hodson 1988, 1990; Hofstein 1988; Hofstein & Lunetta 1982; Igelsrud & Leonard 1988; Ivins 1983; Lazarowitz & Tamir 1994; Pushkin 1997.

The Learning Cycle

Background

For many science educators, the pattern of instruction known as the learning cycle is most associated with the work of the Science Curriculum Improvement Study (SCIS) during the late 1950s and early 1960s, although concurrently, Chester Lawson, a geneticist and biology educator at Michigan State University, independently identified a similar pattern. The term itself did not appear until about 1970 when it was used in SCIS Teacher's Guides.

The phases of the learning cycle vary both in name and number as well as explicitness. Most describe a three-phase instructional cycle and the following terms are used: Exploration, Term Identification, and Concept Application. These are terms for teachers, not students. During the first phase, *Exploration*, students learn through direct interaction with materials. Teacher guidance is minimized; the purpose is to arouse curiosity, raise questions through conceptual conflict, and identify patterns. In the second phase, *Term Identification*, students discuss the data collected, clarify the pattern(s) observed, and are provided the appropriate terminology. This phase is sometimes referred to as Concept Label but since concepts are mental patterns which must be perceived and constructed by students, the best a teacher can do is introduce the term associated with the concept. In the third phase, *Concept Application*, students apply and extend the range of the concept. This is done through laboratory work, readings, demonstrations, problems, etc.

> *"The learning cycle is one method of teaching that purports to be consistent with the way people spontaneously construct knowledge.... In a real sense, recent work into inquiry methods of instruction represents not a novel departure from past practices, but a growing awareness of how we should teach and why we should teach in a particular way."*
>
> Lawson, 1994

What Research Says

- The learning cycle approach has been shown to be effective in promoting positive attitudes toward science and science instruction, understanding content, improving the use of science process skills, and advancing reasoning skills at the elementary, middle school, high school, and college level.
- While physics students prefer the learning cycle sequence, it has been shown that the sequence is unimportant provided all three phases are taught. For chemistry students, it is more complicated. When new concepts are introduced, all students learn them better if terms are introduced following exploration. For review concepts, it depends on whether the student is still at the concrete or formal operational stage. For concrete operational students, term introduction should be last; for formal operational students, term introduction should occur first.
- In general, all three phases—exploration, term identification, concept application—are necessary. In addition, students prefer this complete learning sequence. The exploration and term identification phases are more effective than the term identification phase alone.
- Does format, i.e., laboratory vs. non-manipulative activities make a difference? For physics students, the answer is no, although they prefer using laboratory apparatus to reading. For those chemistry students who are still concrete operational, the laboratory format is superior to reading or lecture. For formal operational students, the reading format is as effective. But for all chemistry students, laboratories must provide data that leads to the concept, and laboratory instruction must include term identification and discussion.

Implications for the Classroom

- The traditional approach is to 1) verbally introduce students to the content to be learned; 2) have students verify what they have just been told through a "recipe" hands-on activity; and 3) complete the lesson with a teacher-led discussion, the assignment of related problems and/or having students apply what they have learned through another structured activity.
- Implement the learning cycle by 1) using the materials and/or laboratory first (Exploration); 2) discussing and helping students summarize what they have learned from the laboratory experience and *then* introducing the appropriate terms (Term Identification); and 3) having students apply what they have learned through another exploration activity or a student generated experiment or a report or a field trip or a class debate/role play or…(Concept Application).
- Use discussion of exploration activities to find out what students think about what they did, how they summarized and interpreted data, and the evidence for their conclusions.
- To help students become more autonomous learners and to assume more responsibility for their learning, something many students will resist, your questions should make use of wait time and require extended answers, not yes or no, agree or disagree. Answers to students' questions should not be the kind that they can answer themselves and many times the best answer is another question.
- The learning cycle is useful in sequencing and selecting content. Questions a planner might ask include: What is the big idea of this unit and/or lesson in the unit? What concepts and processes should be taught? In what order? At what level? What alternative conceptions are students likely to bring to the learning? (Learning cycle instruction makes direct use of them rather than avoiding them or pretending that they do not exist. It treats them as alternative hypotheses to be tested.) What is the role of text and technology materials? How will the big idea be assessed? Through a portfolio or a performance or an interview or a concept map or…?
- Lawson, Abraham & Renner (1989) provide three modifications of the learning cycle approach that represent points on a continuum from descriptive to experimental science. These are:

  1. Descriptive learning cycles. Students explore, discover, and describe a pattern. After the data and pattern are discussed, the teacher introduces the appropriate term(s). Finally, additional explorations involving the same concept are made.

  2. *Empirical-Abductive (EA) learning cycles*. Abduction refers to analogical reasoning which is used in these cycles. In the exploration phase students not only answer a descriptive question but also raise a causal question. The data gathered in the exploration are used to test alternative hypotheses advanced by students. Then appropriate terms are introduced and the concepts further explored. EA learning cycles often include the descriptive question, "What factors affect…?" followed by "What causes…?"

  3. Hypothetical-Deductive (HD) learning cycles. These cycles involve explanation of some scientific phenomenon. In the exploration, students (or the teacher) raise a causal question, suggest alternative hypotheses, and design and conduct an experiment to test their hypotheses. During term introduction, data are analyzed and compared, terms are introduced and evidence based conclusions are made. In the concept application phase, other phenomena involving the same concepts are discussed or explored.

EA and HD learning cycles reveal alternative conceptions. The disequilibrium that results can lead to improved understanding of concepts and/or reconstruction of concepts, more connected concepts, greater facility in the use of procedural knowledge, and the use of data to resolve conflicts.

Three For Starters

Colburn, A., & Clough, M. P. (1997, May). “Implementing the learning cycle.” *The Science Teacher*, pp. 30-33.

Lawson, A. E., Abraham, M. R., & Renner, J. (1989). “A theory of instruction: Using the learning cycle to teach science concepts and thinking skills.” *Monograph of the National Association for Research in Science Teaching*, Cincinnati, OH: NARST.

Renner, J. W., & Marek, E. (1988). *The learning cycle and elementary school science teaching*. Portsmouth, NH: Heinemann.

For Further Study

Atkin & Karplus 1962; Francis, Hill & Redden 1991; Ivins 1983; Karplus & Thier 1967; Lawson 1988; Lawson 1994b; Lawson & Renner 1975; Marek & Methven 1991; Renner & Lawson 1973; Rubin & Norman 1992.

Science as Inquiry

Background

Inquiry also appears in the literature as enquiry. The latter spelling is owed to Joseph Schwab (1960), University of Chicago, who more than 30 years ago sought the answer to a compelling question, "What do scientists do all day?" His answer, based on a review of some 2,000 scientific research papers, continues to dominate discussions of practice, although inquiry (or enquiry) remains a slippery goal.

There is an important distinction between general inquiry and scientific inquiry. Being inquisitive, curious, asking questions, solving problems, making decisions, clarifying values, and trying to discover something new (at least to the inquirer) are some characteristics of inquiry in general. Scientific inquiry, the quintessential scientific activity, reflects the nature of science or how scientists play the game of science, or perhaps more accurately how scientists play the *games* of science, for there are different ways of approaching problems and styles of inquiry in biology, chemistry, earth & space sciences, and physics. In addition, theoretical structures in the different disciplines influence what is observed and how it is observed.

> *"In the vision presented by the Standards, inquiry is a step beyond "science as a process," in which students learn skills, such as observation, inference, and experimentation. The new vision includes the 'processes of science' and requires that students combine processes and scientific knowledge as they use scientific reasoning and critical thinking to develop their understanding of science. "*
>
> NRC, 1996

What Research Says

- Welch et al. (1981) summarize their findings of an extensive assessment of the status of science education in the United States in a pithy statement, "There appears to be a discrepancy between existing general statements about the importance of inquiry and the attention given it in practice." The reasons include teacher preparation, classroom management and materials problems, a felt responsibility to prepare students for the next level of schooling and/or testing, confusion over the meaning of inquiry, allegiance to teaching facts, and a belief that inquiry instruction is successful only for above-average ability students. Reasons given by other researchers include limited time and energy, inquiry is too slow, the risk is too high, teaching habits, teacher discomfort, too difficult for most students, the approach lacks sufficient structure, expense, and reading difficulties.
- It has been shown for elementary science programs that disadvantaged students benefit the most from the use of inquiry in terms of science process, science content, attitude, creativity, and language development. Advantaged students benefit to a somewhat lesser extent except on content knowledge. Bredderman (1982) found that programs that "stress content can be expected to outperform students in activity-based programs that stress process. The reverse is true on process tests. All things being equal, you get what you teach for."
- As a generality, at the secondary level, the inquiry-based science curricula of the '60s and '70s have been shown to be superior to traditional curricula on achievement, process skills, problem solving, and attitude. The pattern of results is less clear for chemistry on achievement and process skills. Shymansky et al. (1990) also found that "students developed their process skills and interest in science at the elementary grade level and then increased their achievement and continued their process skill development in later grades."
- While inquiry can help students develop reasoning, higher-level thinking, and the use of science processes, students do not readily differentiate between the theory or the ideas they bring to an investigation and the evidence they have collected.

Implications for the Classroom

- Teaching science as inquiry is used in classroom situations in two different ways. The distinction is between "inquiry as it appears in the scientific enterprise" or *inquiry as content* and "using the method of scientific inquiry to learn some science" or *inquiry as technique* (Rutherford, 1964).
- Inquiry is intimately related to conceptual change, an activity in which scientists are always engaged as they use, clarify, refine, and extend or narrow the range of their understanding and the application of concepts. Inquiries are always embedded in the conceptual systems students bring to them. Inquiries can be used to help students confront the inadequacies of their conceptual systems as well as to help them deepen understandings and increase the density of their conceptual networks. What this means is that conceptual understanding grows; it seldom ends.
- The inquiry level of activities can be determined by using an analytic scheme developed by Tafoya et al. (1980), all of which have their uses in teaching and learning science.

  1. *Confirmation*. The student follows a known, specific procedure to verify a concept or principle, or to learn a technique. The student knows what to expect.

  2. *Structured inquiry*. The student does not know what results to expect beforehand. Procedures are outlined and the activities and materials provided are structured so that the student can discover relationships and make generalizations from the data collected.

  3. *Guided inquiry*. The student is given the problem to investigate but develops the procedures and methods and discovers the concepts or principles.

  4. *Open inquiry*. The student develops the problem and the procedure for solving it, interprets the data, and reaches evidence-based conclusions. Open inquiry requires students to use science concepts or principles.
- Framing suitable research questions is an important skill in scientific inquiry, where well-structured problems do not often exist. This skill requires time and practice. W-M Roth (1994) has shown that students make productive use of narrative descriptions of a phenomenon being explored in their own inquiries and do not have to first narrow their question. He further notes that "the fact that students do not state variables…has been seen as a deficit that needed to be overcome…." He argues that students need first to construct their own meaning and negotiate that meaning with other members of their research group before they engage in stating and isolating variables.
- Storey & Carter (1992) wonder about the need for and continued use of the term hypothesis in student inquiries. They argue that scientists "begin or continue a research project with a question instead of a formal hypothesis." And hypotheses are just as often formulated in mid-study as they are at the beginning. Henry Bauer (1982) wrote that he was shocked when a political scientist told him that the scientific method consisted of setting up hypotheses and testing them, when his mentor in research, who had a respectable international reputation, would simply say, "Let's try this and see what happens."
- Scientific inquiry, this dialogue between the natural world and the inquirer, must take into account the differences between students and scientists. Scientists differ in what they know as well as in their laboratory and field skills (students are far less persistent, too!). Scientific inquiries are forms of argument and the emphasis should be on interpretation and the generation of new questions. Students are learning to participate in the scientific community as apprentices.
- As students construct meaning from their inquiries, not all students, no matter how hard teachers work with them, will arrive at the proper scientific conceptions. This information is usually hidden when conventional, multiple-choice tests are used. What this means for assessment and evaluation is that assessment must be process oriented. What are the contributions of the students? Are the

claims viable in terms of the data collected (including claims made by students who enter and pursue blind alleys in their research)? How creative are the research questions? Are the findings consistent with currently held views? What skills did the students use, and how well were they used in the process of finding answers to questions?

Three For Starters

Lowery, L. F. (Ed.) (1997). *NSTA pathways to the science standards: Guidelines for moving the vision into practice. Elementary School Edition*. Washington, DC: National Science Teachers Association.

Texley, J., & Wild, A. (Eds.) (1996). *NSTA pathways to the science standards: Guidelines for moving the vision into practice. High School Edition*. Washington, DC: National Science Teachers Association.

Storey, R. D., & Carter, J. (1992, December). “Why the scientific method?” *The Science Teacher*, pp. 18-21.

For Further Study

Bauer 1982; Bredderman 1982, 1985; Costenson & Lawson 1986; National Research Council 1995; Project 2061 1993; K. J. Roth 1989; W-M Roth & Roychoudhury 1993; Rutherford 1964; Schwab 1960; Shymansky, Hedges & Woodworth 1990; Tafoya, Sunal, & Knecht 1980; Welch, Klopfer, Aikenhead & Robinson 1981.

Science for All

Background

"All students regardless of age, gender, cultural or ethnic background, disabilities, aspirations or interest and motivation in science should have the opportunity to attain high levels of scientific literacy."

NRC, 1996

"Science for All" is the central theme of current science education reform. The equity principle is referred to throughout the National Science Education Standards document. This emphasis is a reminder that equity remains a persistent challenge and an elusive goal in science teaching and learning. Although it is not as obvious, historians of curriculum point out that science for all was also an expected outcome of the major science education reforms of the 1960s, especially after the initial focus on the high school disciplinary sciences. Clearly, this was not achieved. Many students learned that they could not learn science and that it was not for them.

"All" certainly seems clear enough. At the second annual SciMath^{MN} Assembly (1996), Rodger Bybee, Director of the Center for Science, Mathematics and Engineering Education at the National Research Council, recalled a comment he made in a discussion of equity: "What is it that you don't understand about 'all'?" "All" includes the obvious populations: gifted and talented, boys and girls, students "at risk," students who are learning English as a second language, minorities, those with disabilities, and the more than 97 percent of students who will not be career scientists.

However, "all" also includes a curriculum dimension—the science curriculum that is appropriate for all children — and this will not occur easily or without some struggle. The nature of this curriculum is aptly characterized by Angelo Collins (1995) who writes that both scientists and science teachers "are asked to re-imagine science as experienced by all students. My experience leads me to believe that this kind of re-imagining is not trivial."

What follows are selected highlights of a rich and diverse literature. The categories are somewhat artificial and in many cases a statement found in one could easily be included in another. It also needs to be emphasized that teaching all students for understanding is a variegated and complex enterprise. There is a great need for studies that tell us more about how to help all children learn and develop a sense of understanding, one on which informed practice can be based.

This summary tends to be general rather than specific. What science for all means when it comes to specific classrooms or schools is not completely clear. To some, the phrase may indicate a single, all-encompassing instructional and curriculum approach, perhaps recalling the effective teaching research movement which attempted to identify generic teaching practices. What seems more likely is a variety of focused efforts, especially as we learn more about the heterogeneity of students and the practices that promote their conceptual understanding. If you are interested in specific issues you will have to do—indeed you must do—your own research. It is hoped that the references will provide some help in this effort.

What Research Says

At Risk

- For students at risk of dropping out of school, science and mathematics achievement and enrollment is low.
- Holding students to high academic standards will not cause them to fail or harm their self-esteem.
- Policies, such as retaining low achieving students in grade, placing them in special education, or assigning them to lower tracks, frequently backfire.
- At risk students are more heterogeneous than previously suspected and require very different interventions.

Special Needs

- Accurate classification of children is difficult and classification systems used to place children in special programs are problematic.
- There is a small to moderate beneficial effect of inclusive education on the academic and social outcomes of children with special needs.
- Segregating special needs children in separate classrooms has a negative effect on both academic performance and social adjustment.

Gifted and Talented

- Accelerating the instruction of able students promotes their intellectual development. It is not harmful and does not harm their social or emotional development.
- Areas of concern in gifted education include the labeling of gifted learners, the grading of gifted learners, underachieving gifted students, disadvantaged gifted students, culturally diverse gifted learners, disabled gifted learners, gifted females, and career education for the gifted.
- Optimal development requires the active involvement of the learner; written materials, lectures, etc., are not in themselves appropriate to learning concepts. The sensory stimulation that results from active involvement is needed at both the elementary and secondary levels.
- Gifted students need many opportunities and time for reflection to make sense of their experiences to fully master scientific inquiry.

Girls

- Research has tended to focus on a deficiency model that identifies weaknesses and treats girls learning science as if they were the problem. This has led to considerations of how to make girls more aggressive, analytical, competitive, etc., or what one researcher has called “remedial masculinity.” An efficacy model of what girls can do has shown that many of the “problems” lie in science classrooms as well as within our broader culture. There is *no* evidence that biological differences are responsible for the gender gap in science.
- Teachers’ verbal behaviors influence what boys and girls believe they can achieve, e.g., differential encouragement of girls and boys based on the assumption that girls dislike science or that science is not suitable for them, allowing girls to be in control of technology, encouraging girls to act as experts, calling primarily on boys (by name as contrasted to girls who are not as frequently called by name) to answer questions as well as providing them more feedback, and interventions to insure that both boys and girls have the same opportunities for the “hands-on” part of science.
- Between ages 9 and 14, girls’ science achievement declines and their interest in science wanes. Attitudes toward science are strongly differentiated by the time a student reaches 11 years of age. However, boys and girls start off equal in their interest in science in school.
- Girls are reluctant to guess when taking tests.
- Girls tend to be more interested than boys in topics that relate to people and their problems as well as to connecting mathematics and science to the everyday world.
- There are significant differences between the number of boys and girls who have made scientific/technological equipment, made something from junk, and used even simple scientific equipment such as barometers, scales, thermometers, compasses, and meter sticks.

Limited English Proficiency (LEP)

- There is a tendency to place LEP students in low ability classes rather than consider their actual abilities.
- LEP students learn most proficiently when they are taught English across the curriculum. It is especially productive to integrate science and English teaching. Hands-on science learning promotes language development.
- Students must be encouraged to write as much as possible, both in their home language and in English. It is difficult to move to higher and higher levels of abstraction without the support of language connections.
- The same type of teaching and learning experiences do not work equally effectively for all cultural groups.

Minority

- Research has shown that poor performance in science and mathematics is not attributable to inherent characteristics of student populations.
- There is little research on how different cultures view science.
- Minorities suffer most from standardized tests and textbook tests where instruction is most closely keyed to these tests. Because of the pressure to improve students' test scores, curriculum and instruction tends to focus on drill rather than the reasoning skills of mathematics and science.
- If norms and expectations are low, student outcomes are also likely to be low.
- The positive motivation of elementary students toward learning and school is not sustained by many adolescents.
- Native American and comparable reference populations have more similar than dissimilar learning styles although Native American students are more visual.
- Native American students show a significantly more positive attitude toward both Native Americans and science when taught science using culturally relevant materials.
- There is little research on the context/format of the learning that occurs in non-majority homes and how it might be used in educating children.

Implications for the Classroom

There is one consistent, recurring theme in the literature: quality science teaching at any level and for all students is experience-based. Science is an active process, a verb, "sciencing." This kind of science is for all students. This provides an environment for both academic and social interaction, one that depends on the use and development of students' reasoning abilities.

At Risk

- It is misguided to focus on the mastery of basic skills before asking students to achieve higher-order skills. Instruction in basic skills must be seen as part of the larger task of learning to think well.
- Instruction in basic skills must be done in concert with the larger task of learning higher-order skills.

Special Needs

- Learning experiences should be as multi-sensory as is safe and possible. Such experiences have an added benefit, too. They are effective with almost all students.
- Instruction should include direct experience with the materials of science.

Gifted

- There should be a strong emphasis on inquiry-based science learning. The inquiries should be authentic and original.
- Content mastery should occur within the context of the processes of science.
- Students should have opportunities to interact in significant ways with practicing scientists as mentors and teachers.

Girls

- Science should be connected to humanistic concerns. Since girls are more likely to express uncertainty about the advantages and disadvantages of science and technology to society, these issues provide fertile opportunities for learning about the nature of science, the applications of science and technology, and how to make value judgments that draw on what is being learned in science.
- Pairing girls with girls provides opportunities for more girls to manipulate equipment and to use equipment that they may not have encountered before.
- Cooperative learning strategies are very useful ways for girls to learn science, but they must include teaching on how to work together effectively.
- Observe your questioning patterns and be sure that you are equitable in terms of the ways you interact with boys and girls as well as in the kinds of questions you ask of them.

Limited English Proficiency (LEP)

- While science works well for teaching English, it is important to teach science as a way of knowing and thinking. Laboratory work provides time for conversation about new concepts as well as materials with which to experience and explore them. Because the materials and data are at hand, students can also explain their reasoning in detail.
- Traditional multiple-choice, standardized tests are widely used with LEP students. They emphasize facts rather than the ability to understand and apply them. The assessments must also reflect the "hands-on" instruction characteristic of inquiry-based science.

Minorities

- Science education should include the use of culturally relevant content. Atwater (1995a-c) and Banks (1987, 1988) have proposed several ways to integrate culturally relevant content into the curriculum. The value of using such approaches is that they can improve the conversation about beliefs in science and hone beliefs about science for all students.
- Students should be given opportunities to do science rather than read about it. Doing science includes reasoning about science. This kind of science emphasizes the active role of the learner in constructing knowledge.
- Science instruction should not be isolated from the rest of the students' lives. The contextualization of tasks can make a difference in performance. Many science experiences are those of a special world, confusing, often counterintuitive and counter to daily experience. When students can participate in and observe science in the ordinary world in which they live, they are more likely to learn as

well as come to appreciate science as a way of knowing. When this can be embedded in a cultural context, the possibilities for new understandings and connections becomes even stronger.

Three For Starters

National Science Teachers Association (NSTA) (1991, October/November). "NSTA position paper on multicultural education." *NSTA Reports!*, p. 7.

National Science Teachers Association (NSTA) (1994, March). "Special Issue: Science for all." Science Scope.

Rodriquez, A. J. (1997, January). Invited paper. *The Science Teacher*, p.8.

For Further Study

ASCD 1994/1995; Atwater 1993, 1995a, b, c; Banks 1987, 1988; Bybee 1996; Cole 1995; Collins 1995; Doebler & Mardis 1980/1981; Erickson & Erickson 1984; Feldhusen, VanTassel-Baska & Seeley 1989; Harris 1995; Holden 1992; Matthews & Smith 1994; Oakes 1990; Shepardson & Pizzini 1991; Simons & Hepner 1992.

Also see p. 6-29 through 6-33 of the MN K-12 Science Framework for SciMath^{MN} Equity Statement and selected resources for improving equity in science education.

Science/Technology/Society (STS)

Background

In 1859, the British philosopher, Herbert Spencer, in a widely read and cited essay entitled "What Knowledge is of Most Worth?", called for "one more science (in addition to biology, chemistry, and physics)…the Science of Society," the interaction of science, technology, and society (STS). The idea was largely ignored until about 1900. Since then, STS has been the subject of controversy and has been included in an inevitable variety of committee recommendations and reports about the wisdom of providing students a discipline-centered curriculum or a science curriculum with an STS orientation, one focusing on real-world problems.

The STS educational view re-emerged, this time to a much wider audience of science educators, in 1982 and again in 1990, when the NSTA Board of Directors unanimously approved position papers on STS, "a new effort providing appropriate science for all." STS was defined as the teaching and learning of science in the context of human experiences. The 1982 position paper recommended that science instruction should include minimums for science-related social issues: 5% in elementary, 15% in middle school, and 20% in high school. The time recommendations disappeared in 1990. The new position paper noted that "there are no concepts and/or processes unique to STS; instead STS provides a setting and a reason for considering basic science and technology concepts and processes. STS means determining and experiencing ways that these basic ideas and skills can be observed in society."

The NSES content standards provide an answer that is similar to Spencer's on what a scientifically literate person should know and be able to do. However, the NSES content standards broaden the answer to Spencer's question. They not only include science as inquiry, physical science, life science, and earth and space science but also include science and technology, science in personal and social perspectives, history of science, and unifying concepts and processes. Science educators have both the opportunity and responsibility to organize this content using a variety of topics and perspectives.

"These are turbulent times in the history of science education. Influential elements in society such as government and industry are demanding more science for schools so that future citizens can comprehend a science- and technology-oriented society. At the same time the field of science education is critically re-examining what kind of school science experience that should be. Within this context, an influential and highly visible new movement, the "Science-Technology-Society" (STS) movement is beginning to consolidate a particular kind of solution to what many educators regard as a crisis in school science, that is, a disjuncture between school science and the kind of science background required by citizens in post-industrial society."

Hart & Robottom, 1990

What Research Says

There is not yet as large a body of research on the effects of STS approaches as there are assertions and rhetoric in favor of STS education. However, there are some important findings. In comparison with traditional science classes, students in STS classes:

- do as well, not better nor worse, in the attainment of concepts.
- do better on process, application, creativity, and attitude assessment items.
- significantly improve in their understanding of social issues and STS interactions.
- significantly improve their attitudes toward science, science classes and learning. Girls show a positive attitude change that is three times that found in non-STS classrooms.
- show gains in thinking skills provided the skills are both practiced and assessed.
- do not compromise their achievement in future classes at a higher grade level or university. This effect is most noticeable for the more academically talented students.

Implications for the Classroom

Glen Aikenhead (1994) has developed a useful set of categories describing approaches to teaching science through STS content and provides a variety of published curriculum examples.

- *Motivation by STS Content*. STS content is mentioned in order to make lessons more interesting and to show applications of science. It is not considered as STS instruction. Students are not assessed on STS content.
- *Casual Infusion*. STS study is attached to a science topic and ranges in length from 30 minutes to 2 hours. There is little attention paid to curricular cohesiveness. Students may be assessed although it is superficial.
- *Purposeful Infusion of STS Content*. While the science content is traditional, the 30 minute to 2 hour STS studies are integrated into the curriculum. Students are assessed to some degree.
- *Singular Discipline Through STS Content*. STS content is used to organize the discipline although the science content looks similar to a traditional science course (there may be less of it). Students are assessed on STS content.
- *Science Through STS Content*. The science content is a result of STS content but the topics are selected from a variety of science courses. Student assessment still emphasizes science content although their understanding of STS content is also assessed.
- *Science Along with STS Content*. Relevant science content is used for enrichment; the focus is on STS issues. Assessment is about equally divided between science and STS.
- *Infusion of Science into STS Content*. STS is the instructional focus. Science tends to be restricted to broad concepts of science. The primary assessment is on STS content.
- *STS Content*. The focus is the study of a technology and social issue. Science, if mentioned at all, is used primarily to show linkages. There is almost no assessment of science content.

Three For Starters

Aikenhead, G. (1994). “What is STS teaching?” In J. Solomon & G. Aikenhead (Eds.), *STS education* (pp. 47-59). New York, NY: Teachers College Press, Columbia University.

Lowery, L. F. (Ed.) (1997). *NSTA pathways to the science standards: Guidelines for moving the vision into practice. Elementary School Edition*. Washington, DC: National Science Teachers Association.

Texley, J., & Wild, A. (Eds.) (1996). *NSTA pathways to the science standards: Guidelines for moving the vision into practice. High School Edition*. Washington, DC: National Science Teachers Association.

For Further Study

Aikenhead 1994; Bybee, Harms, Ward, & Yager 1980; Good, Renner, Lawson & Herron 1984/1985; Hart & Robottom 1990; McConnell 1982; NSTA 1982, 1990; Ogens 1991; Solomon & Aikenhead 1994; Spencer 1859; Yager 1983, 1983/1984, 1990a, 1990b, 1993; Yager & Tamir 1992.

Taking Students' Prior Understanding Into Account

Background

Our awareness of the conflict between children's conceptions about the world and the concepts of science stem from the early work of Piaget, one of many fertile leads he provided. However, it was not until the mid-1970s and the shift that occurred in learning research and theory from behaviorism to constructivism that students' conceptions, their ideas about how the world works, were seriously considered by both science educators and cognitive psychologists.

> *"Unless students can break with their everyday experience in thought, they cannot see the extraordinary range of options for living and thinking; and unless students give up many commonsense beliefs, they may find it impossible to learn disciplinary concepts that describe the world in reliable, often surprising ways."*
>
> Floden, Buchmann & Schwille, 1987

Because humans are knowledge makers and not merely passive knowledge absorbers, learning results from their interaction with materials, content, and prior experience. This means that students bring their own ideas into classrooms. Some of these ideas can interfere with learning science.

The prior, but scientifically incorrect ideas that learners hold about science are referred to by a great variety of names, e.g., children's science, preconceptions, naive conceptions, intuitive science, alternative frameworks, etc. One of the most common terms for them is misconceptions, but because this has a pejorative connotation, some researchers reserve this term for misunderstandings that are a result of instruction. These researchers refer to concepts that children bring to class based on their life experience as alternative conceptions.

Most of the research on alternative conceptions and misconceptions has been done in the physical sciences, particularly on the laws of motion, but there is a rich and growing literature in both the life and earth and space sciences.

The idea that concepts change is not restricted to beginning learners. It is central to science. An example of the process of conceptual change in a scientist is found in the life of Charles Darwin, specifically during the period from 1831-1838 in which his view of a static world in which organisms did not evolve changed to one of interaction of the physical and biological world and their evolution (cf. Gruber & Barrett, 1974).

What Research Says

- Science educators have underestimated the power of the conceptions about science and mathematics that students bring to their school learning.
- Students have very rich prior knowledge about many of the science/mathematics concepts they study in school. These prior concepts are pervasive.
- Student concepts make sense when viewed from the perspective of their everyday experience, but these views are not compatible with scientific and mathematical ways of exploring and thinking about phenomena.
- Students often end instruction with the same understanding of concepts that they had prior to instruction. Prior concepts about how science works are tenacious and often difficult to modify.
- Instruction that takes the ideas of students seriously is far more likely to be successful than instruction that ignores them.
- Using the learning cycle helps learners make the transition from their prior understandings to the concepts of science.
- The use of bridging analogies which link a known example of the concept to an unknown example helps to change conceptions.

- Instructional strategies that produce dissatisfaction with a prior conception and show the adequacy and power of the scientific conception have been found to be effective in promoting conceptual change. These strategies create conceptual conflict and are consistent with a constructivist approach.
- The impact of laboratory/inquiry activities on conceptual change has not received as much research attention as strategies designed to bring students into conceptual conflict with the ideas they hold and the ideas scientists hold. There is evidence that the laboratory/inquiry activities can help students to examine and change their beliefs about concepts. This is also consistent with constructivism and a commitment to self-regulated learning.

Implications for the Classroom

Because students are not blank slates when they come to the classroom, their alternative conceptions can be used as an instructional resource.

- Students should be asked for their ideas. Experiments should include students making a prediction, then recording their observations, and comparing and reconciling their prediction with their observations. This can also be done at the beginning of a particular unit or class discussion. By making ideas explicit, learners clarify them and are more likely to modify their beliefs based on careful consideration of data.
- Prior conceptions about the ideas of science make sense; they work. While scientifically wrong, they are based on reason and experience or, as one researcher put it, they are “intelligently wrong.” The classroom atmosphere must be one of respect as students explain their thinking about their ideas and the evidence they collect.
- Investigations in science must allow students to test their alternatives. This suggests that exploration of cul-de-sacs may be valuable. It will certainly help students understand the nature of science.
- Conceptual change is not easy or automatic and students must be provided time and opportunities to resolve differences between predictions and evidence that counters them. In many cases, more than one experience must be provided to convince students about scientific ways of knowing.
- When possible, “school stuff” should be connected with “stuff from the everyday world” of students. Both science and mathematics are often seen as restricted to the requirements of classroom and school rather than having something to do with so-called “real life”.
- Students should have opportunities to investigate their questions: The answers must come from doing something with the materials of science. They should develop hypotheses, make predictions, draw conclusions based on evidence, and evaluate the concepts they hold with respect to the data they have collected.
- Teaching for conceptual change requires the use of multiple modes of assessment. These certainly can include traditional knowledge tests but will also have to include other kinds of tests such as those including questions that require explanations or the construction of concept maps.
- The major reform documents in science education emphasize a focus on key concepts, those that are central to the discipline, rather than covering a lot of details.
- Not all students will change their ideas. It takes time and multiple experiences to grow understanding.

Three For Starters

Ault, Jr., C. R. (1984, April). “Intelligently wrong: Some comments on children’s misconceptions.” *Science and Children*, pp. 22-24.

Project 2061. *American Association for the Advancement of Science*. (1993). “Chapter 15: The research base.” Washington, DC: Author.

Wandersee, J. H., Mintzes, J. J., & Novak, J. D. (1993). “Research on alternative conceptions in science.” pp. 177-210 in D. L. Gabel (Ed.), *Handbook of research on science teaching and learning: A project of the National Science Teachers Association*. New York: Macmillan.

For Further Study

Driver 1989; Eaton, Anderson & Smith 1983; Floden, Buchmann & Schwille 1987; Gruber & Barrett 1974; Guzzetti, Snyder, Glass & Gamas 1993; Minstrell 1982a, 1982b, 1982c; Minstrell & Smith 1983; Nussbaum & Novick 1982; Pfundt & Duit 1991; Watson & Konicek 1990; Westbrook & Rogers 1996.

Thinking Styles

Background

In spite of the fact that humans vary in terms of abilities, interests, and preferences, the traditional educational system appears to have assumed that learners cluster around some relatively homogeneous average. It wasn't until the late 1970s that a significant body of literature challenging this assumption as well as professional development opportunities began to appear on the topics of learning and teaching styles and their implications for learning.

"Most children assume that knowledge just happens to them, that it is handed to them by some parent-like seer as if it were a peanut butter and jelly sandwich. Rarely are they asked how they learned something and how their way may be special."

Sizer, 1984

What Research Says

- Style is not an ability but a preference.
- There is a human tendency to think that others are more like us than they really are, i.e., that humans think the same way about the same things or share the same teaching and learning styles.
- A characteristic of style is its variation. Style can vary according to tasks, stage in life, even as a result of our role models. While we often prefer to learn or teach things in a certain way, style is not nearly as fixed as is commonly believed.
- When learners experience only one type of learning style, some learners are at an advantage while others are at a disadvantage.
- Ability and style are easily confused by both teachers and learners, i.e., a perceived lack of ability may be a style difference.
- Style is easily confused with groups/gender/culture/race. Such confusion can lead to stereotypes. It is much easier to predict which concepts are better learned through concrete experience than it is to predict which students learn best through concrete experience. The same holds for groups.
- Differences in teachers' styles vary across schools, grades, and subject matter.
- When teacher style and student style match, students are more likely to receive higher grades and favorable evaluations than when they do not.

Implications for the Classroom

- There are a great variety of instruments used to assess learning styles, such as the self assessment inventories developed by Anthony Gregorc (1982, 1985). Similarly, there are a variety of tools developed by educators to provide a bridge to style-differentiated learning, as in the work of Kathleen Butler (1984) and that of Bob Samples, Bill Hammond and Bernice McCarthy (1985).
- Rather than using preference inventories, Robert Sternberg (1994) suggests making use of student preferences for instruction, assessment, and learning activities. Like the fashion industry but with a different agenda, he suggests changing thinking and learning styles often so that all students benefit. An example, one of paramount concern, is assessment. Assessments are not intrinsically good or bad, although they can be good or bad examples of particular assessment types. If you are interested in whether students know their facts, fact-oriented multiple-choice tests are appropriate and they benefit certain children. If you are interested in whether students can do an inquiry, then a performance assessment is the more authentic measure and it also likely to benefit certain children. If you are interested in students' understanding of science, then multiple formats must be included, thus increasing the chances that all students will be able to show you what they know. What is crucial is matching assessment to the outcome. It is clear that if a student's learning is to be adequately assessed, a collection of different kinds of assessments must be used. Sternberg's model is based on mental self-government. The basic idea is simple enough; we govern ourselves. Governments and government vary: legislative, executive, judicial, monarchic, hierarchic, and oligarchic. Sternberg's model includes 13 styles. In the assessment example above, students who do well and

like multiple-choice tests exhibit an executive and conservative style. Students who like to do many things at once show an oligarchic style and often need help in setting priorities. Students who show an anarchic style need help in learning to use more organized approaches to their learning.

- Instructional methods must match the outcome you have in mind. For example, there are times to lecture, ask questions, use groups, assign problems, do projects, and use small groups for discussion or for recitation.
- The key to taking learning styles into account is to thoughtfully and systematically vary the approach.

Three For Starters

Samples, B., Hammond, B. & McCarthy, B. (1985). *4Mat and science: Toward wholeness in science education*. Barrington, IL: Excel, Inc.

Sternberg, R. J. (1994, November). “Allowing for thinking styles.” *Educational Leadership*, pp. 36-40.

Usiskin, Z. (1993). “Individual differences in the teaching and learning of mathematics.” *USCMP Newsletter*, No. 14. Chicago, IL: University of Chicago.

For Further Study

Butler 1984 ; Caine & Caine 1991; Carbo, Dunn & Dunn 1978; Dunn, Dunn & Price 1981; Cornet 1983; Davidman 1981; Gardner 1985; Gregorc 1982, 1985; Price 1979; Renzulli & Smith 1978; Samples, Hammond & McCarthy 1985; Sizer 1984.

BEST PRACTICE

Wait Time

Background

In the late 1960s, Mary Budd Rowe (1973) analyzed more than 300 tape recordings of a variety of science instruction. She found that teachers asked questions at the rate of two or three per minute; that students must reply within one second or the questions will be repeated, rephrased or answered by someone else; and that once an answer is given, teachers respond within 0.9 seconds by either asking another question or responding to the answer.

Rowe referred to the period of silence that follows teachers' questions as "wait time." There are two kinds of wait time. Wait Time 1 is the pause after a question by a teacher and Wait Time 2 is the pause after a student's response to the question. A characteristic of Wait Time 2 is that student responses occur in bursts: talk-pause-talk-pause. Some 20 percent of teacher responses to Wait Time 2 consisted of rewards ("Good," "OK," "Nice") and sanctions ("You know better," "Think!").

> *"The authority for changing ideas comes from the results of experiments. Students have to learn to trust their ability to find answers. They have to feel safe in asking questions. They need time to think and a safe environment in which to speculate."*
>
> Rowe, 1973

Rowe found that when wait times were increased to three seconds or longer, the nature of children's and teacher's conversation changed. It became richer.

What Research Says

- The effects on students of increasing wait time include:
  - The length of student responses increase.
  - Students increase the number of unsolicited, relevant responses.
  - Students ask more questions.
  - The question tone of student responses decreases.
  - The incidence of speculative thinking increases.
  - Students use more evidence in their responses.
  - Contributions by "slow" students increase.
- The effects on teachers of increasing wait time include:
  - More reflective and variable questions.
  - More flexibility in responses to students.
  - The total number of questions decreases.
  - Higher expectations for students, especially those rated as "slow learners."
- Research also shows that wait time has an influence on achievement in science. When wait time is increased to three seconds or longer, students perform better on test questions that demand the use of higher-level cognitive abilities.

Implications for the Classroom

- The research studies show that wait times from three to seven seconds are likely to result in more thoughtful answers, provided that the questions are deserving of such answers! These findings hold at all levels as well as across the disciplines: elementary, middle/junior high school, high school, and college.
- Wait time can become a "catch phrase" and mechanical. In practice, it is not always so straightforward. There is a relationship between the amount of wait time and the level of the question. Questions that are low in cognitive demand require shorter wait times than questions that demand more from students. Student expectations can also influence the amount of wait time. Students un-

accustomed to the use of wait time may just sit there and look at the teacher, waiting for her or him to make the next move.

- If you want to study the influence of wait time, record part of a lesson (at least 15 minutes), transcribe it, measure the pauses, and classify the questions and the student responses. Do this again a month later, after you have become experienced with using wait time and compare the responses. Is it worth the effort? What is your evidence? Is there anything else you need to know? Do you agree with Rowe's findings?

Three For Starters

Rowe, M. B. (1974a). "Wait-time and rewards as instructional variables, their influence on language, logic and fate control: Part I, Fate Control." *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.

Tobin, K. (1985). "The effect of an extended teacher wait time on science achievement." *Journal of Research in Science Teaching*, *17*:469-475.

References

Altier & Duell 1991; Fagan, Hassler & Szabo 1981; Gabel 1995; Riley 1986; Rowe 1969, 1973, 1996; Tobin 1985, 1986, 1987.

References

Abbot, J. (1997, March). “To be intelligent.” *Educational Leadership*. pp. 6-10.

Aikenhead, G. (1994a). “What is STS teaching?” In J. Solomon & G. Aikenhead (Eds.), *STS education* (pp. 47-59). New York, NY: Teachers College Press, Columbia University.

Aikenhead, G. (1994b). “Consequences to learning science through STS: A research perspective.” In J. Solomon & G. Aikenhead (Eds.), *STS education* (pp. 169-186). New York, NY: Teachers College Press, Columbia University.

Airasian, P. W. & Walsh, M. E. (1997, February). “Constructivist cautions.” *Phi Delta Kappan*. pp. 444-449.

Altiere, M. A. & Duell, O. K. (1991). “Can teachers predict their students’ wait time preferences?” *Journal of Research in Science Teaching*, *28*:455-461.

Anderson, C. W. (1992). “Strategic teaching in science.” In M. K. Pearsall (Ed.), *Scope, sequence and coordination of secondary school science. Volume II: Relevant research*, (pp. 221-236). Arlington, VA: National Science Teachers Association.

Anderson, H. (1991). “Y’all can.” *Science Scope*, *14(8)*:28-31.

Applegate, J. (1995). “Cooperative learning in graded tests.” *The American Biology Teacher*, *57*:363-364.

Arons, A. B. (1984, May). “The ‘crisis’ that never went away.” *Journal of College Science Teaching*, pp. 397-398.

Association for Supervision and Curriculum Development (ASCD) (1994/1995, December/January). “The inclusive school.” *Educational Leadership*. Single topic issue: Author.

Atkin, J. M. & Karplus, R. (1962, September). “Discovery or invention?” *Science Teacher*, pp. 45, 47, 49, 51.

Atwater, M. M. (1993, March). “Multicultural science education.” *The Science Teacher*, pp. 33-37.

Atwater, M. M. (1995a, February). “The multicultural science classroom. Part I: Meeting the needs of a diverse student population.” *The Science Teacher*, pp. 21-23.

Atwater, M. M. (1995b, April). “Part II: Assisting all students with science acquisition.” *The Science Teacher*, pp. 42-45.

Atwater, M. M. (1995c, May). “Part III: Preparing science teachers to meet the challenges of multicultural education.” *The Science Teacher*, pp. 26-29.

Ault, Jr., C. R. (1984, May). “Intelligently wrong: Some comments on children’s misconceptions.” *Science & Children,* pp. 22-24.

Baines, L. (1997, March). “Future Schlock: Using fabricated data and politically correct platitudes in the name of education reform.” *Phi Delta Kappan*. pp.493-498.

Banks, J. A. (1987). *Teaching strategies for ethnic studies, 4th edition*. Boston, MA: Allyn and Bacon.

Banks, J. A. (1988, Spring). “Approaches to multicultural curriculum reform.” *Multicultural Leader*, pp. 1-4.

Baron, J. B. (1993). “Epilogue.” In J. B. Baron (Ed.) *Assessment as an opportunity to learn* (pp. 3-14). Hartford, CT: Connecticut State Department of Education.

Bates, G. R. (1978). “The role of laboratory in secondary school science programs.” In M. B. Rowe (Ed.), *What research says to the science teacher*. Arlington, VA: National Science Teachers Association.

Bauer, H. H. (1982, June). “What do we mean by ‘scientific?’” Paper presented to the Society for Scientific Exploration.

Baxter, G. T. & Shavelson, R. J. (1994). “Science performance assessments: Benchmarks and surrogates.” *International Journal of Educational Research*, *21*, 279-289.

Brandt, R. (1997, March). “On using knowledge about our brain: A Conversation with Bob Sylwester.” *Educational Leadership*, pp.16-19.

Berenson, S. B. & Carter, G. S. (1995). “Changing assessment practices in science and mathematics.” *School Science and Mathematics*, *95*, 182-186.

Bredderman, T. (1982). “The effects of activity-based science in elementary schools.” In M. B. Rowe (Ed.), *Education in the 80’s: Science* (pp. 63-75). Washington, DC: National Education Association.

Bredderman, T. (1985). “Laboratory programs for elementary school science: A meta-analysis of effects on learning.” *Science Education*, *69*, 577-591.

Brooks, J. G., & Brooks, M. G. (1993). *The case for constructivist classrooms*. Alexandria, VA: Association for Supervision and Curriculum Development.

Brush, S. G. (1974). “Should the history of science be rated X?” *Science, 183*, 1164-1172.

Brush, S. G. (1989). “History of science and science education.” *Interchange*, *20*(2), 60-70.

Butler, K. A. (1984). *Learning and teaching style: In theory and practice*. Maynard, MA: Gabriel Systems, Inc.

Bybee, R. W., & Sund, R. B. (1982). *Piaget for Educators* (2nd ed.). Columbus, OH: Charles E. Merrill.

Bybee, R. W., Harms, N., Ward, B., & Yager, R. (1980). "Science, society, and science education." *Science Education*, 64, 377-395.

Caine, R.N. (1990, October). "Understanding a brain-based approach to learning and teaching." *Educational Leadership*, pp. 66-70.

Caine, R.N. (1995, April). "Reinventing schools through brain-based learning." *Educational Leadership*, pp. 43-47.

Caine, R. N., & Caine, G. (1991). *Making connections: Teaching and the human brain*. Alexandria, VA: Association for Supervision and Curriculum Development.

Caine, R.N. & Caine, G. (1997). *Education on the edge of possibility*. Alexandria, VA: Association for Supervision and Curriculum Development.

Calhoun, E. (1994). *How to use action research in the self-renewing school*. Alexandria, VA: Association for Supervision and Curriculum Development.

Calvin, W.H. (1996). *How brains think: Evolving intelligence, then and now.* New York NY: Basic Books.

Carbo, M., Dunn, R., & Dunn, K. (1986). *Teaching students to read through their individual learning styles*. Englewood Cliffs, NJ: Prentice-Hall.

Clements, D. H., & Battista, M. T. (1990, September). "Constructivist learning and teaching." *Arithmetic Teacher*, pp. 34-35.

Clough, M. (1992, October). "Research is required reading." *The Science Teacher*, pp.36-39.

Cochran, K. F. (1992). "Pedagogical content knowledge: Teachers' transformations of subject matter." In F. Lawrenz, K. Cochran, J. Krajcik, and P. Simpson (Eds.), Research matters…to the science teacher. *NARST Monograph 5* (pp. 3-10). Manhatten, KS: Center for Science Education, Manhatten State University.

Cohen, P. (1995). "Understanding the brain: Educators seek to apply brain research." *Education Update*, *37*(7), 1, 4-5.

Colburn, A. & Clough, M.P. (1997, May). "Implementing the learning cycle." *The Science Teacher*, pp.30-33.

Cole, R. W. (Ed.) (1995). *Educating everybody's children: Diverse teaching strategies for diverse learners*. Alexandria, VA: Association for Supervision and Curriculum Development.

Collins, A. (1996). "National science education standards: Qualities and quandries." In R.W. Bybee (ed.), *National Standards & the Science Curriculum*, pp. 34-39. Dubuque, IA: Kendall/Hunt.

Cornet, C. (1983). "What you should know about teaching and learning styles." *Phi Delta Kappan*. Fastback 191.

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

Cushing, J. T. (1989). "A tough act: History, philosophy, and introductory physics." *Interchange, 20*(2), 54-59.

Davidman, L. (1981, May). "Learning style: The myth, the panacea, the wisdom." *Phi Delta Kappan*, pp. 641-645.

Deutsch, M. (1962). "Cooperation and trust: Some theoretical notes." In M. Jones (Ed.), *Nebraska Symposium on Motivation* (pp. 175-319). Lincoln, NE: University of Nebraska Press.

Doebler, L. K. & Mardis, L. J. (1980/1981). "Effects of a biological education program for Native American children." *NABE Journal*, *5*(2), 23-28.

Donaldson, M. (1979, March). "The mismatch between school and children's minds." *Human Nature*, pp. 60-67.

Doran, R. L. (1990a, May). "What research says…about assessment." *Science & Children*, pp. 26-27.

Doran, R. L. (1990b, September). "What research says…about appropriate methods of assessment." *Science & Children*, pp. 42-45.

Driver, R. (1982). *The pupil as a scientist?* Milton Keynes, UK: Open University Press.

Driver, R. (1987). "Promoting conceptual change in classroom settings: The experience of the children's learning in science project." In J. D. Novak (Ed.), *Proceedings of the second international seminar on misconceptions and educational strategies in science and mathematics*. Ithaca, NY: Cornell University.

Driver, R. (1989). "Students' conceptions and the learning of science." *International Journal of Science Education*, *11*, 48-490.

Driver R., & Bell, B. (1986). "Students' thinking and the learning of science: A constructivist view." *School Sciences Review*, *67*, 443-456.

Dunn, R., & Dunn, K. (1978). *Teaching students through their individual learning styles: A practical approach*. Reston, VA: Reston Publishing Company.

Dunn, R., Dunn, K., & Price, G. E. (1981, May). "Learning styles: Research vs. opinion." *Phi Delta Kappan*, pp. 645-646.

Duschl, R. (1994). "Research on the history and philosophy of science." In D. L. Gabel (Ed.), *Handbook of research in science teaching and learning: A project of the National Science Teachers Association*, (pp. 443-465). New York, NY: MacMillan Publishing Company.

Eisner, E.W. (1997, January). "Cognition and representation." *Phi Delta Kappan*, pp. 349-353.

Eaton, J. F., Anderson, C. W., & Smith, E. L. (1983, April). "When students don't know they don't know." *Science & Children*, pp. 5-6, 8-9.

Erickson, G. & Erickson, L. (1984). "Females and science achievement." *Science Education*, *68*, 63-89.

Fagan, E., Hassler, D., & Szabo, M. (1981). "Evaluation of questioning strategies in language arts instruction." *Research in the Teaching of English*, *15*, 267-273.

Feldhusen, J. & VanTassel-Baska, J. (1989). *Excellence in educating the gifted*. Denver, CO: Love Publishing Co.

Fensham, P. J. (1986/1987, December/January). "Science for all." *Educational Leadership*, pp. 18-23.

Finley, F. N. (1983). "Science processes." *Journal of Research in Science Teaching*, *20*, 47-54

Fischbach, G.D. (1992, September). "Mind and brain. *Scientific American*, pp. 48-58.

Floden, R.E., Buchmann, M., & Schwille, J.R. (1987). "Breaking with everyday experience." *Teachers College Record*, *88*, 485-506.

Fosnot, C. T. (1993). "Rethinking science education: A defense of Piagetian constructivism." *Journal of Research in Science Teaching*, *30*, 1189-1201.

Francis, R. G., Hill, D. M., & Redden, M. G. (1991). "Mathematics and science: A shared learning cycle and a common learning environment." *School Science & Mathematics*, *91*, 339-343.

Gabel, D. (1994). *Handbook of research on science teaching and learning: A project of the National Science Teachers Association*. New York, NY: MacMillan.

Gabel, D. (1995). "Science: Wait time." In G. Cawelti (Ed.), *Handbook of research on improving student achievement*. (p.127). Arlington, VA: Educational Research Service.

Gardner, H. (1985). *Frames of mind: The theory of multiple intelligences*. New York, NY: Basic Books.

Gardner, H. (1991a). "The tensions between education and development." *Journal of Moral Education*, *20*, 113-125.

Good, R., Renner, J. W., Lawson, A. E., & Herron, J. D. (1984/1985, December/January). "Letters: Two views on science education." *Journal of College Science Teaching*, pp. 155-156.

Good, R. G., Wandersee, J. H., & St. Julien, A. J. (1993). "Cautionary notes on the appeal of the new 'ism' (constructivism) in science education." In K. Tobin (Ed.), *The practice of constructivism in science education*, (pp.71-87) Hillsdale, NJ: Lawrence Erlbaum Associates.

Gregorc, A. (1982). *An adult's guide to style*. Maynard, MA: Gabriel Systems, Inc.

Gregorc, A. (1985). *Inside styles: Beyond the basics*. Maynard, MA: Gabriel Systems, Inc.

Grossen, B. (1996, Fall). "Making research serve the profession." *American Educator*, pp. 7-8, 22-27.

Grossen, B. (1996, Fall). "Making research serve the profession." *American Educator*, 7-8, 22-27.

Gunstone, R. F., & Champagne, A. B. (1990). "Promoting conceptual change in the laboratory." In E. Hegarty-Hazel (Ed.), *The student and the curriculum* (pp. 159-182). London, UK: Rutledge.

Gruber, H. E., & Barrett, P. H. (1974). *Darwin on man*. New York, NY: E. P. Dutton.

Guzzetti, B. J., Snyder, T. E., Glass, G. V., & Gamas, W. S. (1993). "Promoting conceptual change in science: A comparative meta-analysis of instructional interventions from reading education and science education." *Reading Research Quarterly*, *28*, 117-155.

Harnisch, D. L. (1994). "Performance assessment in review: New directions for assessing student understanding." *International Journal of Educational Research*, *21*, 341-350.

Harris, J. W. (1995, February). "Sheltered instruction: Bridging the language gap in the science classroom." *The Science Teacher*, pp. 24-27.

Hart, D. (1994). *Authentic assessment: A handbook for educators.* Menlo Park, CA: Addison-Wesley.

Hart, E. P., & Robottom, I. M. (1990). "The science-technology-society movement in science education: A critique of the reform process." *Journal of Research in Science Teaching*, *27*, 575-588.

Haury, D. L. (1993). "Teaching science through inquiry." *ERIC/CSMEE Digest*, EDO-SE-93-4. ERIC/CSMEE, Columbus, OH.

Hein, G. E., & Price, S. (1994). *Active assessment for active science: A guide for elementary school teachers*. Portsmouth, NH: Heinemann.

Herman, J. L., Aschbacher, P. R., & Winters, L. (1992). *A practical guide to alternative assessment*. Reston, VA: Association for Supervision and Curriculum Development.

Hirsch, Jr., E. D. (1996, Fall). "Reality's revenge: Research and ideology." *American Educator*, pp. 4-6, 31-46.

Hodson, D. (1988). "Experiments in science and science teaching." *Educational Philosophy and Theory*, *20*, 53-66.

Hodson, D. (1990). "A critical look at practical work in school science." *The School Science Review*, *70*, 33-40.

Hofstein, A. (1988). "Practical work and science education II." In P. Fensham (Ed.), *Development and dilemmas in science education*. (pp. 189-216). London, UK: Falmer.

Hofstein, A., & Lunetta, V. (1982). "The role of the laboratory in science teaching: Neglected aspects of research." *Review of Educational Research*, *52*, 201-217.

Holden, C. (1992). "Study flunks science and math tests." *Science*, pp. 258:541.

Igelsrud, D., & Leonard, W. H. (1988). "Labs: What research says about biology laboratory instruction." *American Biology Teacher*, *50*, 303-306.

Inhelder, B., & Piaget, J. (1958). *The growth of logical thinking from childhood to adolescence*. New York, NY: Basic Books.

Ivins, J. E. (1983, May). "What are your labs really teaching?" *The Science Teacher*, pp. 56-59.

Johnson, D. W., & Johnson, R. T. (1978). "Cooperative, competitive, and individualistic learning." *Journal of Research and Development in Education*, *12*, 3-15.

Johnson, D. W., & Johnson, R. T. (1987). *Learning together and alone: Cooperation, competition and individualization* (2nd ed.). Englewood Cliffs, NJ: Prentice-Hall.

Johnson, D. W., & Johnson, R. T. (1989a). "*Cooperation and competition: Theory and research*. Edina, MN: Interaction Book Company.

Johnson, D. W., & Johnson, R. T. (1989b, April). "Toward a cooperative effort: A response to Slavin." *Educational Leadership*, pp. 80-81.

Johnson, D. W., & Johnson, R. T. (1989/1990, December/January). "Social skills for successful group work." *Educational Leadership*, pp. 29-33.

Johnson, D. W., & Johnson, R. T. (1991). "Group assessment as an aid to science instruction." In G. Kulm & S. M. Malcom (Eds.), *Science assessment in the service of reform* (pp. 283-289). Washington, DC: American Association for the Advancement of Science.

Johnson, D. W., Johnson, R. T., & Holubec, E. J. (1986). *Circles of learning: Cooperation in the classroom* (Revised). Edina, MN: Interaction Book Company.

Johnson, H. C. (1990). "How can the curriculum and evaluation standards for school mathematics be realized for all students?" *School Science and Mathematics*, *90*, 527-543.

Jorgensen, M. (1994) *Assessing habits of mind: Performance-based assessment in science and mathematics*. Columbus, OH: ERIC Clearinghouse for Science, Mathematics, and Environmental Education, The Ohio State University.

Kahle, J. B., & Lakes, M. E. (1983). "The myth of equality in science classrooms." *Journal of Research in Science Teaching*, *21*, 131-140.

Karplus, R., & Thier, H. D. (1967). *A new look at elementary school science*. Chicago: Rand McNally.

Kerns, T., (1996, May). "Should we use cooperative learning in college chemistry? *Journal of College Science Teaching*, pp. 435-438.

Kotulak, R. (1996). *Inside the brain*. Chicago, IL: Andrews and McMeel.

Kromhout, R., & Good, R. (1983). "Beware of societal issues as organizers for science education." *School Science and Mathematics*, *83*, 647-650.

Kyle, Jr., W. C. (1980). "The distinction between inquiry and scientific inquiry and why high school students should be cognizant of the distinction." *Journal of Research in Science Teaching*, *17*, 123-130.

Lang, M.P. (1996, February). Invited paper. *The Science Teacher*.

Lawrenz, F. & Munch, T. W. (1984). "The effect of grouping of laboratory students on selected educational outcomes." *Journal of Research in Science Teaching*, *21*, 699-708.

Lawson, A. E. (1988). "A better way to teach biology." *American Biology Teacher*, *50*, 266-273, 289.

Lawson, A. E. (1994a). *Biology: A critical thinking approach*. Menlo Park, CA: Addison-Wesley.

Lawson, A. E. (1994b). *Science teaching and the development of thinking*. Belmont, CA: Wadsworth.

Lawson, A. E., Abraham, M. R., & Renner, J. (1989). "A theory of instruction: Using the learning cycle to teach science concepts and thinking skills." *Monograph of the National Association for Research in Science Teaching*, No. 1, Cincinnati, OH: NARST.

Lawson, A. E., & Renner, J. W. (1975). "Piagetian theory and biology teaching." *The American Biology Teacher*, *37*, 336-343.

Lazarowitz, R., & Tamir, P. (1994). "Research on using laboratory instruction in science." In D. L. Gabel (Ed.), *Handbook of research on science teaching: A project of the National Science Teachers Association* (pp. 94-128). New York, NY: MacMillan.

Lederman, N.G. (1992a). "Students' and Teachers' Conceptions of the Nature of Science: A Review of the Research." *Journal of Research in Science Teaching*, *29*, 331-359

Lederman, N. G. (1992b). "Improving students' conceptions of the nature of science: The role and influence of the classroom teacher." In F. Lawrenz, K. Cochran, J. Krajck and P. Simpson (Eds.), *Research matters…to the science teacher*. NARST Monograph 5, (pp. 11-17). Manhattan, KS: Science Education Center.

Lederman, N. G., & Niess, M. L. (1996). "Faulty towers." *School Science and Mathematics*. *96*, 337-338.

Lederman, N. G., & Niess, M. L. (1997). "The nature of science: Naturally?" *School Science and Mathematics*. *97*, 1-2.

Lentz, K. A., & Coe, E. J. (1984, March). "Determining levels of concreteness and abstraction." *Science and Children*, pp. 50-52.

Levine, D. (1985, September). "Adding a woman's touch." *The Science Teacher*, pp. 25-29.

Linn, M. C., & Barbules, N. C. (1993). "Construction of knowledge and group learning." In K. Tobin (Ed.), *The practice of constructivism in science education* (pp. 91-120). Hillsdale, NJ: Lawrence Erlbaum Associates.

Lowery, L. F. (1990). "*The biological basis of thinking and learning*." Berkeley, CA: University of California.

Lowery, L.F. (Ed.) (1997). *NSTA pathways to the science standards: Guidelines for moving the vision into practice. Elementary School Section*. Washington, DC: National Science Teachers Association.

Manteuffel. (1980). "The anatomy of student investigations." *The American Biology Teacher*, *42*:462-467.

Marek, E., & Methven, S. (1991). "Effects of the learning cycle upon student and classroom teacher performances." *Journal of Research in Science Teaching*, *28*, 41-53.

Marx, R.W., Bloomfield, PC, Krajcik, J.S., and Soloway, E. (1997) "Enacting project-based science." *The Elementary School Journal. 97*: 341-358.

Matthews, R. (1989). "A role for history and philosophy in science teaching." *Interchange*, *20* (2), 3-15.

Matthews, C. L., & Smith, W. S. (1994). "Native American related materials in elementary science instruction." *Journal of Research in Science Teaching*, *31*, 363-380.

McComas, W. F. (1996). "Ten myths of science: Reexamining what we think we know about the nature of science." *School Science and Mathematics*, *96*, 10-16.

McConnell, M. C. (1982). "Teaching about science, technology and society at the secondary school level in the United States: An educational dilemma." *Studies in Science Education*, *9*:2-32.

Metz, K. E. (1995). "Reassessment of developmental constraints on children's science instruction." *Review of Educational Research*, *65*, 93-127.

Miller, L. (1988). "Unlikely beginnings: The district office as a starting point for developing a professional culture of teaching." In A. Leiberman. (1988) *Building a professional culture in schools*. New York, New York: Teachers College Press.

Minstrell, J. (1982a, January). "Explaining the 'at rest' condition of an object." *The Physics Teacher*, pp. 10-14.

Minstrell, J. (1982b). "Conceptual development research in the natural setting of the classroom." In M. B. Rowe (Ed.) *Education in the 80s: Science*, (pp 129-143). Washington, DC: National Education Association.

Minstrell, J. (1983, January). "Getting the facts straight." *The Science Teacher*, pp. 52-54.

Minstrell, J., & Smith, C. (1983, November/December). "Alternative conceptions and a strategy for change." *Science & Children*, pp. 31, 33.

Moje, E. B., & Handy, D. (1995). "Using literacy to modify traditional assessments: Alternatives for teaching and assessing content understanding." *Journal of Reading*, *38* 612-625.

NRC. (1995). *National Science Education Standards*. Washington, DC: National Academy Press.

National Science Teachers Association (NSTA). (1982). *An NSTA position statement. Science-technology-society: Science education for the 1980s*. Arlington, VA: Author..

National Science Teachers Association (NSTA). (1990). "An NSTA position statement. Science/technology/society: A new effort for providing appropriate science for all." Arlington, VA: Author.

National Science Teachers Association (NSTA). (1991, October/November). "NSTA position paper on multicultural education." *NSTA Reports!*, p.7.

National Science Teachers Association (NSTA). (1994, March). "Special Issue: Science for all." *Science Scope*.

Nussbaum, J., & Novick, S. (1982). "Alternative frameworks, conceptual conflict and accommodation: Toward a principled teaching strategy." *Instructional Science*, *11*:183-200.

Oakes, J. (1990). "Lost talent—the underrepresentation of women, minorities and disabled persons in science." Santa Monica, CA: Rand Corporation.

Ogens, E. M. (1991). "A review of science education: Past failures, future hopes." *The American Biology Teacher*, *53*, 199-203.

Ossont, D. (1993, May). "How I use cooperative learning." *Science Scope*, pp. 28-31.

Padilla, M.J. (1980). "Science activities—for thinking." *School Science & Mathematics*, *LXXX*, 601-608.

Pfundt, H., & Duit, R. (1991). *Bibliography: Student's alternative frameworks and science education* (3rd ed.). Kiel, Germany: University of Kiel.

Piaget, J. (1948). *To understand is to invent*. NY: Viking Press.

Piaget, J. (1954). *The construction of reality in the child*. Translated by M. Cook. NY: Ballantine Books.

Piaget, J. (1957, March). "The child and modern physics." *Scientific American*, pp. 46-51.

Piaget, J. (1962). *Language and thought of the child*. London, UK: Rutledge and Kegan Paul.

Piaget, J. (1970a). *Psychology and epistemology*. NY: The Viking Press.

Piaget, J. (1970b). *Science of education and the psychology of the child*. NY: Grossman Publishing.

Piaget, J. (1970c). *Structuralism*. NY: Basic Books.

Piaget, J. (1973a). *The child and reality*. NY: Grossman Publishers.

Piaget, J. (1973b). *To understand is to invent*. NY: Grossman Publishers.

Piaget, J. (1975). *The development of thought: Equilibration of cognitive structures*. NY: The Viking Press.

Pogrow, S. (1994, November). "Helping students who 'just don't understand.'" *Educational Leadership*, pp. 62-66.

Pogrow, S. (1995, February). "Making reform work for the educationally disadvantaged." *Educational Leadership*, pp. 20-24.

Pogrow, S. (1996, June). "Reforming the wannabe reformers." *Phi Delta Kappan*. pp. 656-663.

Pool, C.R. (1997, March). "Maximizing learning: A conversation with Renate Nummela Caine." *Educational Leadership*, pp. 11-15.

Price, G. (1979). "Learning style manual." Lawrence, KS: Price Systems.

Project 2061. (1993). *Benchmarks for science literacy*. Washington, DC: American Association for the Advancement of Science.

Pushkin, D. B. (1997, February). "Where do ideas for students come from?" *Journal of College Teaching*. pp. 238-242.

Renner, J. W., & Lawson, A. E. (1973, March). "Piagetian theory and instruction in physics." *The Physics Teacher*, pp. 165-169.

Renner, J. W., & Marek, E. (1988). *The learning cycle and elementary school science teaching*. Portsmouth, NH: Heinemann.

Renzuilli, J. S., & Smith, L. H. (1978). *Learning styles inventory*. Storrs, CT: Creative Learning Press.

Riley, II, J. P. (1986). "The effects of teachers' wait-time and knowledge comprehension questioning on pupil's science achievement." *Journal of Research in Science Teaching*, *23*, 335-342.

Roth, K. J. (1984). "Using classroom observations to improve science teaching and curriculum materials." In C. W. Anderson (Ed.), *Observing science classrooms: Perspectives from research and practice. Yearbook of the Association for the Education of Teachers in Science*, (pp. 77-102). Columbus, OH: ERIC/SMEAC.

Roth, K. J. (1989, Winter). "Science education: It's not enough to 'do' or 'relate.'" *American Educator*, pp. 16-22, 46-48.

Roth, K. J. (1992). “Science education: It’s not enough to ‘do’ or ‘relate.’” In M. K. Pearsall (Ed.), *Scope, sequence and coordination of secondary school science. Volume II: Relevant research*, (pp. 151-164). Arlington, VA: National Science Teachers Association.

Roth, W-M. (1994). “Experimenting in a constructivist high school physics laboratory.” *Journal of Research in Science Teaching*, *31*, 197-223.

Roth, W-M. & Roychoudhury, A. (1993). “The development of science process skills in authentic contexts.” *Journal of Research in Science Teaching*, *30*, 127-152.

Rowe, M. B. (1969, March). “Science, silence and sanctions.” *Science and Children*. pp. 35-37.

Rowe, M. B. (1973). *Teaching science as continuous inquiry*. NY: McGraw Hill.

Rowe, M. B. (1974a). “Wait-time and rewards as instructional variables, their influence on language, logic and fate control: Part I, Fate Control.” *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. (1996, September). “Science, silence and sanctions.” *Science and Children*, pp. 35-37.

Rubin, R. L. & Norman, J. T. (1992). “Systematic modeling versus the learning cycle: Comparative effects on integrating science process skill achievement.” *Journal of Research in Science Teaching*, *29*, 715-727.

Russell, T. L. (1981). “What history of science, how much, and why?” *Science Education*, *65*, 51-61.

Rutherford, F.J. (1964). “The role of inquiry in science teaching.” *Journal of Research in Science Teaching*, *2*, 80-84.

Samples, B., Hammond, B. & McCarthy, B. (1985). *4Mat and Science: Toward wholeness in science education*. Barrington, IL: Excel, Inc.

Saner, H., McCaffrey, D., Stecher, B., Klein, S., and Bell, R. (1994). “The effects of working in pairs in science performance assessments.” *Educational Assessment*, *2*, 325-338.

Schwab, J. J. (1960). “What do scientists do?” *Behavioral Science*, *5*, 1-27.

Schwab, J. J. (1962). “The teaching of science as enquiry.” In J. J. Schwab & P. Brandwein (Eds.), *The teaching of science*. Cambridge, MA: Harvard University Press.

Schwab, J. J. (1965). *The biology teacher’s handbook*. American Institute of Biological Sciences, Biological Sciences Curriculum Study. New York, NY: Wiley.

Scientific American. (1992, September). “Special issue on the brain.” New York, NY: author.

Science and Children. (1994, October). Special supplement on assessment.

Science Scope. (1992, March). Special supplement on assessment.

Scott, L. U., & Heller, P. (1991, January). “Team work.” *The Science Teacher*, pp. 24, 26, 27-28.

Sellin, D. F., & Birch, J. W. (1980). *Educating gifted and talented learners*. Rockville, MD: Aspen Systems Corporation.

Shavelson, R. J., & Baxter, G. P. (1992, May). “What we’ve learned about assessing hands-on science.” *Educational Leadership*, pp. 20-25.

Shavelson, R. J., Carey, N. B., & Webb, N. M. (1990, May). “Indicators of science achievement: Options for a powerful policy instrument.” *Phi Delta Kappan*, pp. 692-697.

Shepardson, D. P., & Pizzini, E. L. (1991, November/December). “Gender bias in the classroom—a self evaluation.” *Science and Children*, pp. 38-41.

Shulman, L. S. (1986). “Those who understand: Knowledge growth in teaching.” *Educational Researcher*, *15*(2), pp. 4-14.

Shulman, L. S. (1987). “Knowledge and teaching: Foundations of the new reform.” *Harvard Educational Review*, *57*, 1-22.

Shymansky, J. A., Hedges, L. V., & Woodworth, G. (1990). “A reassessment of the effects of inquiry-based science curricula of the 60s on student performance.” *Journal of Research in Science Teaching*, *27*, 127-144.

Shymansky, J. A., Kyle, Jr., W. C., & Alport, J. (1982). “Research synthesis on the science curriculum projects of the sixties.” *Educational Leadership*, *40*(1), 63-66.

Siegal, M. (1991). *Knowing children: Experiments in conversation and cognition*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Simons, G. G., & Hepner, N. (1992, September). “The special student in science.” *Science Scope*, pp. 32-39, 54.

Sizer, T. (1984). *Horace’s compromise: The dilemma of the American high school*. Boston, MA: Houghton-Miflin Co.

Slavin, R. E. (1983). *An introduction to cooperative learning*. New York, NY: Longman.

Slavin, R. E. (1988, October). “Cooperative learning and student achievement.” *Educational Leadership*, pp. 31-33.

Slavin, R. E. (1989/1990, December/January). “Research on cooperative learning: Consensus and controversy.” *Educational Leadership*, pp. 22-28.

Slavin, R. E., Madden, N. A., & Stevens, R. J. (1989/1990, December/January). “Cooperative learning models for the 3 R’s.” *Educational Leadership*, pp. 22-28.

Smith, E. L., & Anderson, C. W., (1984). “Plants as producers: A case study of elementary school science teaching.” *Journal of Research in Science Teaching*, *21*, 685-695.

Solomon, J. (1994b). “Learning STS and judgments in the classroom: Do boys and girls differ?” In J. Solomon & G. Aikenhead (Eds.), *STS Education*, (pp. 141-154). New York: Teachers College Press, Columbia University.

Solomon, S., & Aikenhead, G. (Eds.) (1994). *STS education: International perspectives on reform*. New York, NY: Teachers College Press, Columbia University.

Sparks-Langer, G. M. & Colton, A. B. (1991, March). “Synthesis of research on reflective thinking.” *Educational Leadership*, pp. 37-44.

Spencer, H. (1859). “Education: Intellectual, moral and physical.” New York, NY: John B. Alden.

Stepans, J. (1984). “Teaching mathematics using the learning cycle.” *Journal of Developmental Education*, *8*(2), 6-8.

Stenmark, J. K. (Ed.) (1991). *Mathematics assessment: Myths, models, good questions, and practical suggestions*. Reston, VA: National Council of Teachers of Mathematics.

Sternberg, R. J. (1982). “Teaching scientific thinking to gifted children.” *Roeper Review*, *4*(4), 4-6.

Storey, R. D., & Carter, J. (1992, December). “Why the scientific method?” *The Science Teacher*, pp. 18-21.

Subbotsky, E. V. (1993). *Foundations of the mind: Children’s understanding of reality*. Cambridge, MA: Harvard University Press.

Tafoya, E., Sumal, D. W., & Knecht, P. (1980). “Assessing inquiry potential: A tool for curriculum decision makers.” *School Science & Mathematics*, *80*,43-48.

Texley, J. & Wild, A. (Eds.) (1996). *NSTA pathways to the science standards: Guidelines for moving the vision into practice*. High School Edition. Washington, DC: National Science Teachers Association.

Tobin, K. (1985). “The effect of an extended teacher wait time on science achievement.” *Journal of Research in Science Teaching*, *17*, 469-475.

Tobin, K. (1986). “Effects of teacher wait time on discourse characteristics in mathematics and language arts classes.” *American Educational Research Journal*, *32*, 191-200.

Tobin, K. (1987). “The role of wait time on higher cognitive learning.” *Review of Educational Research*, *57*, 69-95.

Tobin, K. (1990). “Research on science laboratory activities: In pursuit of better questions and answers to improve learning.” *School Science and Mathematics*, *90*, 403-418.

Tobin, K. (Ed.) (1993). “The practice of constructivism in science education.” Washington, DC: American Association for the Advancement of Science.

Usiskin, A. (1993). “Individual differences in the teaching and learning of mathematics.” *USCMP Newsletter*, No. 14. Chicago, IL: University of Chicago.

Vico, G. 1858 (1710). *De antiquissima Italorum sapientia*. Stamperia de’ Classici Latini. Naples, Italy.

Von Glasersfeld, E. (1989). “Facts and the self from a constructivist point of view.” *Poetics*, *18*, 435-448.

Watson, B., & Konicek, R. (1990, May). “Teaching for conceptual change: Confronting children’s experience.” *Phi Delta Kappan*, pp. 680-685.

Welch, W. W., Klopfer, L. E., Aikenhead, G. S., & Robinson, J. T. (1981). “The role of inquiry in science education: Analysis and recommendations.” *Science Education*, *65*, 33-50.

Westbrook, S. L. & Rogers, L. N., (1996). “Doing is believing: Do laboratory experiences promote conceptual change?” *School Science & Mathematics*, *96*, 263-271.

Wiggins, G. (1989a, May). “A true test: Toward more authentic and equitable assessment.” *Phi Delta Kappan*, pp. 703-713.

Wiggins, G. (1989b). “The futility of trying to teach everything of importance.” *Educational Leadership*, *46*(9), 44-48, 57-59.

Wiggins, G. (1993). *Assessing student performance: Exploring the purpose and limits of testing*. San Francisco, CA: Jossey-Bass Publishers.

Willis, S. (1995, March). “Teachers as researchers,” *Education Update*, *1*, 4-5.

Wills, C. (1993). *The runaway brain: The evolution of human uniqueness*. London, United Kingdom: Basic Books.

Worthen, B. R. (1993). "Critical issues that will determine the future of alternative assessments." *Phi Delta Kappan*, *74*, 444-454.

Yager, R. E. (1983). "In defense of societal issues as organizers for school science." *School Science and Mathematics*, *83*, 651-653.

Yager, R. E. (1983/1984, December/January). "Toward new meaning for school science." *Educational Leadership*, pp. 12-18.

Yager, R. E. (1984/1985, December/January). "Letters: An alternative view." *Journal of College Science Teaching*, pp. 223-224.

Yager, R. E. (1990a, March). "A new approach to science instruction." *Middle School Journal*, pp. 46-48.

Yager, R. E. (1990b, March). "STS: Thinking over the years." *The Science Teacher*, pp. 52-55.

Yager, R. E. (1991, September). "The constructivist learning model." *The Science Teacher*, pp. 52-57.

Yager, R. E. (Ed.) (1993). "The science, technology, society movement." *What Research Says to the Science Teacher*, 7. Arlington, VA: National Science Teachers Association.

Yager, R. E., & Tamir, P. (1992). "Accomplishing STS instruction and the student learning that results." In M. O. Thirunarayanan (Compiler). *Handbook of science, technology and society. Volume 1. A theoretical and conceptual overview of science, technology and society education* (pp. 46-66). Tempe, AZ: College of Education, Arizona State University.

Zahovrik, J. A. (1997, March). "Encouraging—and challenging—students' understanding." *Educational Leadership*, pp. 30-32.