The Laboratory in Science Education: Foundations for the Twenty-First Century

AVI HOFSTEIN
Department of Science Teaching, The Weizmann Institute of Science,
Rehovot 76100, Israel

VINCENT N. LUNETTA
Science Education, The Pennsylvania State University, University Park,
PA 16802, USA

Received 23 June 2002; revised 10 January 2003; accepted 25 January 2003

ABSTRACT: The laboratory has been given a central and distinctive role in science education, and science educators have suggested that rich benefits in learning accrue from using laboratory activities. Twenty years have been elapsed since we published a frequently cited, critical review of the research on the school science laboratory (Hofstein & Lunetta, *Rev. Educ. Res.* **52**(2), 201–217, 1982). Twenty years later, we are living in an era of dramatic new technology resources and new standards in science education in which learning by inquiry has been given renewed central status. Methodologies for research and assessment that have developed in the last 20 years can help researchers seeking to understand how science laboratory resources are used, how students' work in the laboratory is assessed, and how science laboratory activities can be used by teachers to enhance intended learning outcomes. In that context, we take another look at the school laboratory in the light of contemporary practices and scholarship. This analysis examines scholarship that has emerged in the past 20 years in the context of earlier scholarship, contemporary goals for science learning, current models of how students construct knowledge, and information about how teachers and students engage in science laboratory activities. *Sci Ed* **88:**28–54, 2004;
DOI 10.1002/sce.10106

INTRODUCTION

Twenty years ago, we published a frequently cited review entitled "The Role of the Laboratory in Science Teaching: Neglected Aspects of Research," in the *Review of Educational Research* (Hofstein & Lunetta, 1982). We reported that for over a century, the laboratory had been given a central and distinctive role in science education, and science educators have suggested that there are rich benefits in learning that accrue from using laboratory activities. In the late 1970s and early 1980s, some educators began to seriously question both the effectiveness and the role of laboratory work, and the case for the laboratory was not as self-evident as it seemed (see, for example, Bates, 1978). Our 1982

Correspondence to: Vincent N. Lunetta; e-mail: vnl@psu.edu

review provided perspectives on the issue of the science laboratory through a review of the history, goals, and research findings regarding the laboratory as a medium for instruction in introductory science teaching and learning. We wrote

> Science educators (e.g., Schwab, 1962; Hurd, 1969; Lunetta & Tamir, 1979) have expressed the view that uniqueness of the laboratory lies principally in providing students with opportunities to engage in processes of investigation and inquiry.

The 1982 review raised another issue regarding the definition of the goals and objectives of the laboratory in science education. A review of the literature revealed that by and large these objectives were synonymous with those defined for science learning in general. Thus, we suggested that it is vital to isolate and define goals for which laboratory work could make a unique and significant contribution to the teaching and learning of science. We wrote that while the laboratory provides a unique medium for teaching and learning in science (p. 212)

> researchers have not comprehensively examined the effects of laboratory instruction on student learning and growth in contrast to other modes of instruction, and there is insufficient data to confirm or reject convincingly many of the statements that have been made about the importance and the effects of laboratory teaching. The research has failed to show simplistic relationships between experiences in the laboratory and student learning.

Our 1982 review identified several methodological shortcomings in the science education research, that inhibited our ability to present a clear picture regarding the utility of the science laboratory in promoting understanding for students. These shortcomings included

- insufficient control over procedures (including expectations delivered by the laboratory guide, the teacher, and the assessment system);
- insufficient reporting of the instructional and assessment procedures that were used;
- assessment measures of students' learning outcomes inconsistent with stated goals of the teaching and the research; and
- insufficient sample size in many studies, especially in quantitative studies.

Ten years later, Tobin (1990) prepared a follow-up synthesis of research on the effectiveness of teaching and learning in the science laboratory. He proposed a research agenda for science teachers and researchers. Tobin suggested that meaningful learning is possible in the laboratory if the students are given opportunities to manipulate equipment and materials in an environment suitable for them to construct their knowledge of phenomena and related scientific concepts. In addition, he claimed that, in general, research had failed to provide evidence that such opportunities were offered in school science. Four years later, Roth (1994) suggested that although laboratories have long been recognized for their potential to facilitate the learning of science concepts and skills, this potential has yet to be realized.

TWENTY YEARS LATER: NEW PROBLEMS, OPPORTUNITIES, AND SOLUTIONS

In 2002, as this paper is written, we are in a new era of reform in science education. Both the content and pedagogy of science learning and teaching are being scrutinized, and new standards intended to shape meaningful science education are emerging. The *National Science Education Standards* (National Research Council [NRC], 1996) and other science education literature (Bybee, 2000; Lunetta, 1998) emphasize the importance of rethinking the role and practice of laboratory work in science teaching. This is especially appropriate because in recent decades we have learned much about human cognition and learning (Bransford, Brown, & Cocking, 2000). In addition, learning by *inquiry* (NRC, 2000) is posing challenges for teachers and learners (Krajcik, Mamlok, & Hug, 2001). *Inquiry* refers to diverse ways in which *scientists* study the natural world, propose ideas, and explain and justify assertions based upon evidence derived from scientific work. It also refers to more authentic ways in which *learners* can investigate the natural world, propose ideas, and explain and justify assertions based upon evidence and, in the process, sense the spirit of science.

We have based this analytical review of the literature associated with laboratory/practical work in science education, in part, on our review published twenty years earlier (Hofstein & Lunetta, 1982). In this review, we examine changes in the relevant scholarship during the intervening 20 years. In the 1980s, multiple reports were published by prominent groups and authors identifying "crisis" and calling for reform in science education (see, for example, Harms & Yager, 1981; Hurd, 1983; Kyle, 1984; Press, 1982; Yager, 1984). In addition, in the first half of that decade, meta-analysis studies were published that examined the effectiveness of science education curricula developed during the 1960s; for example, Shymansky, Kyle, and Alport (1983) conducted a meta-analytic investigation on students' performance in science resulting from schooling using the science curricula developed in the 1960s. Although their study showed some positive effects of these curricula on students' science learning, the impact was limited because of shortcomings in dissemination and implementation of these curriculum projects.

In the 20 years since our 1982 review was published, the science education community has substantially expanded knowledge of students' understanding of science concepts and of the nature of science. There has also been a substantial paradigm shift in thinking about the ways in which learners construct their own scientific knowledge and understanding. In addition, substantive developments in social science research methodologies enable much richer examination of laboratory and classroom processes and of students' and teachers' ideas and behaviors. Furthermore, throughout the past 20 years the exponential growth of high-technology tools has powerful implications for teaching, learning, and research in the school laboratory.

Used properly, the laboratory is especially important in the current era in which *inquiry* has re-emerged as a central style advocated for science teaching and learning (NRC, 1996, p. 23):

> Inquiry is a multifaceted activity that involves making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results. Inquiry requires identification of assumptions, use of critical and logical thinking, and consideration of alternative explanations.

The term *inquiry* has been used in multiple ways in the science education literature. It has been used somewhat broadly to refer to learning science in classrooms and labs in which the students and their teachers explore and discuss science in a "narrative of enquiry" context. As the science education field develops, it is increasingly important to define and use technical terms like *inquiry* in the learning of science with greater precision and consistency, and progress to these ends is visible in recent scholarship.

The National Science Education Standards in the United States and other contemporary science education literature continue to suggest that school science laboratories have the potential to be an important medium for introducing students to central conceptual and procedural knowledge and skills in science (Bybee, 2000). Hodson (1993) emphasized that the principal focus of laboratory activities should not be limited to learning specific scientific methods or particular laboratory techniques; instead, students in the laboratory should use the methods and procedures of science to investigate phenomena, solve problems, and pursue inquiry and interests. Baird (1990) is one of several persons who has observed that the laboratory learning environment warrants a radical shift from teacher-directed learning to "purposeful-inquiry" that is more student-directed.

In preparing the current review the authors consulted several databases to identify the most appropriate studies and reviews addressing issues associated with teaching and learning in the school science laboratory. This review examined associated science projects, investigations, and practical activities both inside and outside school walls, when such activities were perceived as formal elements of the school science curriculum. In the process, the authors conducted searches of published papers (1982–2001), the ERIC database (1982–2001), dissertation abstracts (1982–2001), and presentations in NARST conferences (1995–2001). In particular, we considered reviews that had been published on the subject of practical work in the intervening years: Blosser (1983), Bryce and Robertson (1985), Tobin (1990), Hodson (1993), and Lazarowitz and Tamir (1994).

In this review, we define science laboratory activities as learning experiences in which students interact with materials and/or with models to observe and understand the natural world. As noted earlier, the review focuses on developments that have occurred since our 1982 review of research on the laboratory was published. Principal sections and issues included in this review are as follows:

- Learning science in the laboratory with special attention to *scholarship associated with models of learning, argumentation and the scientific justification of assertions, students' attitudes, conditions for effective learning, students' perceptions of the learning environment, social interaction, and differences in learning styles and cognitive abilities.*
- Goals for learning, discrepancies, and matching goals with practice with special attention to: *goals for learning, students' perceptions of teachers' goals, teachers' expectations and behavior, the laboratory guide, incorporating inquiry empowering technologies, simulations and the laboratory, assessing students' skills and understanding of inquiry, and the politics of schooling.*
- Teacher education and professional development.
- Synthesis and implications.

LEARNING SCIENCE IN THE SCHOOL LABORATORY

Models of Learning and Their Application

The 1982 paper was written near the end of two decades during which *Piagetian theory* (Karplus, 1977) had served as a principal model for interpreting the nature of science learning and for developing science teaching strategies and curriculum. In reviewing the literature we wrote (Hofstein & Lunetta, 1982) that it was difficult to identify a simple relationship between students' science achievement and their work with materials in the laboratory. During the 1980s the centrality of Piagetian models diminished and attention was increasingly focused on a developing *constructivist* view of learning.

Several studies had shown that often the students and the teacher are preoccupied with technical and manipulative details that consume most of their time and energy. Such preoccupation seriously limits the time they can devote to meaningful, conceptually driven inquiry. In response, Woolnough (1991) wrote that for these reasons, the potential contribution of laboratory experiences to assist students in constructing powerful concepts has generally been much more limited than it could have been. Such comments have been made often throughout the past 20 years.

Tobin (1990) wrote that "Laboratory activities appeal as a way of allowing students to learn with understanding and, at the same time, engage in a process of constructing knowledge by doing science" (p. 405). This important assertion may be valid, but current research also suggests that helping students achieve desired learning outcomes is a very complex process. According to Gunstone (1991), using the laboratory to have students restructure their knowledge may seem reasonable but this idea is also naïve since developing *scientific* ideas from practical experiences is a very complex process. Gunstone and Champagne (1990) suggested that meaningful learning in the laboratory would occur if students were given sufficient time and opportunities for interaction and reflection. Gunstone wrote that students generally did not have time or opportunity to interact and reflect on central ideas in the laboratory since they are usually involved in technical activities with few opportunities to express their interpretation and beliefs about the meaning of their inquiry. In other words, they normally have few opportunities for *metacognitive* activities. Baird (1990) suggested that these metacognitive skills are "learning outcomes associated with certain actions taken consciously by the learner during a specific learning episode" (p. 184). Metacognition involves elaboration and application of one's learning, which can result in enhanced understanding. According to Gunstone, the challenge is to help learners take control of their own learning in the search for understanding. In the process it is vital to provide opportunities that encourage learners to ask questions, suggest hypotheses, and design investigations—"minds-on as well as hands-on." There is a need to provide students with frequent opportunities for feedback, reflection, and modification of their ideas (Barron et al., 1998). As Tobin (1990) and Polman (1999) have noted, in general, research has not provided evidence that such opportunities exist in most schools in the United States, or, for that matter, in other countries.

A *constructivist* model currently serves as a theoretical organizer for many science educators who are trying to understand cognition in science (Lunetta, 1998), i.e., learners construct their ideas and understanding on the basis of series of personal experiences. Learning is an active, interpretive, iterative process (Tobin, 1990). Moreover, there is a growing sense that learning is contextualized and that learners construct knowledge by solving genuine and meaningful problems (Brown, Collins, & Duguid, 1989; Polman, 1999; Roth, 1995; Wenger, 1998; Williams & Hmelo, 1998). Experiences in the school laboratory can provide such opportunities for students if the expectations of the teacher enable them to engage intellectually with meaningful investigative experiences upon which they can construct scientific concepts within a community of learners in their classroom (Penner, Lehrer, & Schuble, 1998; Roth & Roychoudhury, 1993). A social constructivist framework has special potential for guiding teaching in the laboratory. Millar and Driver (1987) were among those who recommended the use of extended, reflective investigations to promote the construction of more meaningful scientific concepts based upon the unique knowledge brought to the science classroom by individual learners. An assumption is that when students interact with problems that they perceive to be meaningful and connected to their experiences, and when teachers are guided by what we know about learning, the students can begin to develop more scientific concepts in dialogue with peer investigators.

Research has also suggested that while laboratory investigations offer important opportunities to connect science concepts and theories discussed in the classroom and in textbooks with observations of phenomena and systems, laboratory inquiry alone is not sufficient to enable students to construct the complex conceptual understandings of the contemporary scientific community. “If students’ understandings are to be changed toward those of accepted science, then intervention and negotiation with an authority, usually a teacher, is essential” (Driver, 1995). Van den Berg, Katu, and Lunetta (1994) reported that hands-on activities with introductory electricity materials in clinical studies with individual students facilitated their understanding of relationships among circuit elements and variables. The activities provided clear tests of the validity of the subject’s ideas. “Frequently they led to cognitive conflict. However, the carefully selected practical activities alone were not sufficient to enable the subject to develop a fully scientific model of a circuit system.” The findings suggested that greater engagement with conceptual organizers such as analogies and concept maps could have resulted in the development of more scientific concepts in basic electricity. Several researchers including Dupin and Joshua (1987) have reported similar findings. When laboratory experiences are integrated with other metacognitive learning experiences such as “predict–explain–observe” demonstrations, etc. (White & Gunstone, 1992) and when they incorporate the manipulation of ideas instead of simply materials and procedures, they can promote the learning of science.

Pursuing that theme in *Designing Project-Based Science: Connecting Learners Through Guided Inquiry*, Polman (1999) conducted an extended case study of a teacher who created a collaborative learning community and provided his high school students with opportunities to “learn by doing” *authentic* science in a science classroom. The teacher was guided by constructivist pedagogy giving special attention to *collaborative visualization*. Polman’s analysis provides detailed information about the teacher’s strategies and behaviors while implementing a *Project-Based Science* model. Polman discussed the teacher’s efforts to organize and support his students in various stages of inquiry learning such as in *asking researchable questions* and in *gathering, analyzing, and presenting data* to construct and justify scientific responses to those questions. Polman also discussed the difficulty and complexity of changing practices by describing conflicts that emerged when the teacher, who was the subject of the study, challenged conventional approaches to teaching and learning science. He demonstrated how the structural and cultural realities of the school complicated the enactment of pedagogical innovation in general and the *Project-Based Science* model, in particular. Polman suggested that teachers who wish to foster science learning through projects and inquiry must play a complex role in discourse with their students.

While there have been substantial developments in scholarship that can guide the development of teaching and curriculum, that scholarship has had only marginal impact on schools. In a summary of five studies that focused on *Project-Based-Learning*, Williams and Hmelo (1998) wrote (p. 266)

> Although several decades of research have given us a strong theoretical basis about the nature of learning and the value of problem-based methods, this information has had relatively small impact on education practices. We do not, as yet, have a widely accepted theory of instruction or carefully thought out manageable methods of implementation consistent with constructivist theory.

To acquire a more valid understanding of these important issues, science educators need to conduct more intensive, focused research to examine the effects of specific school laboratory experiences and associated contexts on students’ learning. The research should examine the teachers’ and students’ perceptions of purpose, teacher and student behavior, and the resulting perceptions and understandings (conceptual and procedural) that the students construct. Research and development projects like those conducted by Polman (1999) and by Krajcik et al. (2000) offer examples of what is needed.

Argumentation and the Scientific Justification of Assertions

Developing assertions about the natural world in school science and then justifying those assertions with data collected in investigations within or beyond the science classroom walls is considered increasingly to be an important element of school science learning (see, for example, Newton, Driver, & Osborne, 1999; Zeidler, 1997). The *National Science Education Standards* (NRC, 1996) also indicates the importance of engaging learners in describing and in using observational evidence and current scientific knowledge to construct and evaluate alternative explanations "based on evidence and logical argument" (p. 145). Engaging in scientific argumentation assists students in constructing meaningful science concepts and in understanding how scientists develop knowledge of the natural world. Driver, Newton, and Osborne (2000) have written that weighing and interpreting evidence, thinking about alternatives, and assessing the viability of scientific claims are essential elements of scientific argumentation and of school science. These experiences are part of students' "enculturation" into science. "Argumentation is particularly relevant in science education since a goal of scientific inquiry is the generation and justification of knowledge claims, beliefs, and actions taken to understand nature" (Jimenez-Aleixandre, Rodriguez, & Duschl, 2000). As elaborated later in the *Inquiry Empowering Technologies* section of this review, new technology tools such as *Progress Portfolio* (Loh et al., in press) can help students negotiate, support explanations and assertions about relationships, connect their findings to driving questions in their investigations, and struggle with the significance of their data (Land & Zembal-Saul, in press). Examining and elaborating the nature of scientific argumentation in general, the utility of engaging students in these processes, and the most appropriate ways to engage students in meaningful argumentation in the laboratory and school science are contemporary domains for research in science education that should have important implications for science teaching and curriculum.

Students' Attitudes

Several studies published in the 1970s and early 1980s reported that students enjoy laboratory work in some courses and that laboratory experiences have resulted in positive and improved student *attitudes* and *interest* in science. Shulman and Tamir (1973) wrote "We are entering an era when we will be asked to acknowledge the importance of affect, imagination, intuition and attitude as outcomes of science instruction as at least as important as their cognitive counterparts" (p. 1139). Nevertheless, beginning in the 1980s, the pendulum of scholarly research attention within the science education literature moved away from the affective domain and toward the cognitive domain in general and toward conceptual change in particular. Two comprehensive reviews that were published in the early 1990s (Hodson, 1993; Lazarowitz & Tamir, 1994) did not discuss research focused on affective variables such as attitudes and interest. Nevertheless, the science education literature continues to articulate that laboratory work is an important medium for enhancing attitudes, stimulating interest and enjoyment, and motivating students to learn science. The failure to examine effects of various school science experiences on students' attitudes is unfortunate since experiences that promote positive attitudes could have very beneficial effects on interest and learning. The failure to gather such data is especially unfortunate in a time when many are expressing increasing concerns about the need for empowerment of women and underrepresented minority people in pure and applied science fields.

Conditions for Effective Learning

In the 1982 review, we pointed out the importance of examining the uniqueness of the science laboratory learning environment in research. We wrote (p. 212)

> Since creating a healthy learning environment is an important goal for many contemporary science educators, there is a need for further research that will assess how time spent in laboratory activities and how the nature of students' activities in the laboratory affect the learning environment.

The science laboratory is central in our attempt to vary the learning environment in which students develop their understanding of scientific concepts, science inquiry skills, and perceptions of science. The science laboratory, a unique learning environment, is a setting in which students can work cooperatively in small groups to investigate scientific phenomena. Hofstein and Lunetta (1982) and Lazarowitz and Tamir (1994) suggested that laboratory activities have the potential to enhance constructive social relationships as well as positive attitudes and cognitive growth. The social environment in a school laboratory is usually less formal than in a conventional classroom; thus, the laboratory offers opportunities for productive, cooperative interactions among students and with the teacher that have the potential to promote an especially positive learning environment. The learning environment depends markedly on the nature of the activities conducted in the lab, the expectations of the teacher (and the students), and the nature of assessment. It is influenced, in part, by the materials, apparatus, resources, and physical setting, but the learning environment that results is much more a function of the climate and expectations for learning, the collaboration and social interactions between students and teacher, and the nature of the inquiry that is pursued in the laboratory.

Students' Perceptions of the Laboratory Learning Environment

The need to assess the students' perceptions in the science laboratory was approached seriously by a group of science educators in Australia (Fraser, McRobbie, & Giddings, 1993), who developed and validated the Science Laboratory Environment Inventory (SLEI). This instrument, consisting of eight learning environment scales, was found to be sensitive to different approaches to laboratory work, e.g., high inquiry or low inquiry and different science disciplines such as biology or chemistry, etc (Hofstein, Cohen, & Lazarowitz, 1996).

The SLEI has been used in several studies conducted in different parts of the world. One comparative study examined students' perceptions in six countries: United Kingdom, Nigeria, Australia, Israel, United States, and Canada (Fraser & McRobbie, 1995). Fraser, McRobbie, and Giddings (1993) in Australia, found that students' perceptions of the laboratory learning environment accounted for significant amounts of the variance of the learning beyond that due to differences in their abilities. In Israel, in the context of chemistry and biology learning, Hofstein, Cohen, and Lazarowitz (1996) used a Hebrew version of the SLEI. They compared students' perceptions of the *actual* and *preferred* learning environment of laboratories in chemistry and biology classes. They found significant differences between chemistry and biology laboratory environments in two scales, namely, *integration*, which describes the extent to which the laboratory activities are integrated with nonlaboratory activities in the classroom and *open-endedness*, which measures the extent to which the activity emphasizes an open-ended approach to investigation. Differences were also found in comparing the students' perceptions of the *actual* and *preferred* learning environments. A more recent study conducted in Israel by Hofstein, Levi-Nahum, and Shore (2001) in the context of learning high school chemistry showed clearly that students who were involved in inquiry-type investigation found the laboratory learning environment to be more *open-ended* and more *integrated* with a conceptual framework than did students in a control group.

If positive students' perceptions of the science laboratory learning environment, i.e., cooperative learning, collaboration, and developing a community of inquiry are among the important intended outcomes of school laboratory experiences, then these outcomes should be assessed by teachers as a regular part of course evaluation. The *science laboratory learning environment inventory* could be used by teachers as one part of *action research* intended to examine the effects of a new laboratory teaching approach or strategy and as part of improving instruction. Researchers can also use this instrument for more summative-type studies in which they examine effects of different kinds of teaching in the laboratory on students' perceptions of the learning environment.

Social Interaction

Science educators increasingly perceive the school science laboratory as a unique learning environment in which students can work cooperatively in small groups to investigate scientific phenomena and relationships. Hofstein and Lunetta (1982), Lazarowitz and Tamir (1994), and Lunetta (1998) suggested that laboratory activities have the potential to enable collaborative social relationships as well as positive attitudes toward science and cognitive growth. As noted earlier in this paper, the more informal atmosphere and opportunities for more interaction among students and their teacher and peers can promote positive social interactions and a healthy learning environment conducive to meaningful inquiry and collaborative learning. The laboratory offers unique opportunities for students and their teacher to engage in collaborative inquiry and to function as a classroom community of scientists. Such experiences offer students opportunities to consider how to solve problems and develop their understanding. Through collaboration, they can also come to understand the nature of an expert scientific community. These are among the learning outcomes now thought to be very important in introductory science.

The importance of promoting *cooperative learning* in the science classroom and laboratory received substantial attention during the 1980s (e.g., Johnson et al., 1981; Johnson & Johnson, 1985; Lazarowitz & Karsenty, 1990) as a way to engage diverse students in collaboration with others in inquiry and to develop a classroom community of scientists. Large numbers of studies demonstrated distinct benefits in students' achievements and productivity when cooperative learning strategies were utilized in the classroom-laboratory. In the intervening years, research intended to examine the effects of student collaboration and the development of "classroom community of scientists" has been increasingly visible. Okebukola and Ogunniyi (1984) compared groups of students who worked cooperatively, competitively, and as individuals in science laboratories and found that the cooperative group outperformed the other groups in cognitive achievement and in process skills. Similarly, Lazarowitz and Karsenty (1990) found that students who learned biology in small cooperative groups scored higher in achievement and on several inquiry skills than did students who learned in a large group class setting. Several papers have reported that the more informal atmosphere and opportunities for more interaction among students and their teacher and peers can promote positive social interactions and a healthy learning environment conducive to meaningful inquiry and collaborative learning (DeCarlo & Rubba, 1994; Tobin, 1990). More recently Land and Zembal-Saul (in press) reported that

> By prompting learners to articulate and connect their experimental findings back to the larger driving questions . . . learners negotiated and struggled with explaining the significance of the data . . . prompting explanation and justification and reflective social discourse.

While promoting and examining reflective social discourse is an important and promising area for further research in science education, observations of science laboratory classrooms today continue to suggest, more often than not, that little attention is given to promoting collaboration, group/community process, and *reflective discourse*.

Differences in Learning Styles and Cognitive Abilities

In general, there has been only limited effort to engage students with diverse abilities, experiences, and needs in sharing their ideas and in collaborative inquiry. Tobin (1986) wrote that the difficulty of tailoring laboratory activities to the needs of diverse students caused some teachers to avoid laboratory investigations, particularly when working with students having low motivation and skill. Dreyfus (1986) made a serious (and rare) attempt to redesign science laboratory activities to be used with mixed ability classes. He suggested that teachers could design investigations to be used effectively by students with different levels of relevant knowledge and with different cognitive abilities. He suggested that teachers who are well informed about their students' abilities should be able to select appropriate approaches and levels of sophistication to align these with their students' needs and abilities. Tailoring school experiences for students with different backgrounds, knowledge, and levels of cognitive ability is especially important in an era in which achieving scientific literacy for all students has become a major goal. Scientific literacy is a central goal, for example, in Benchmarks for Scientific Literacy (American Association for the Advancement of Science [AAAS], 1993) and the *National Science Education Standards* (NRC, 1996) not just in the United States but in the education literature of UNESCO and many other countries as well. At the same time, it is also important for introductory science courses to provide powerful experiences that will encourage and enable students who are so inclined to move toward the frontiers of the pure and applied sciences with well-developed knowledge and skills.

The notion that instructional procedures in science education should be matched to learners' characteristics to maximize the effectiveness of teaching and learning has been widely accepted in the science education scholarly literature, if not in school practice, for many years. In the past 20 years special attention has been given to assessing and developing students' conceptual understanding and other cognitive variables. Simultaneously, less attention has been given to examining variables that influence students' interests and motivation. Hofstein and Kempa (1985), based on a study conducted in Israel by Adar (1969), postulated that a relationship exists between a student's motivational pattern and characteristics (reasons for learning) and his or her preference for certain instructional techniques in the science classroom or laboratory. Kempa and Diaz (1990) probed this relationship. Their study revealed a number of strong relationships between motivational traits and instructional preferences. They found that students they characterized as *conscientious* preferred more *formal* learning environments while others, more motivated by curiosity, enjoyed learning more open-ended situations such as in inquiry laboratory activities. Doing practical work was appealing to the *conscientious* students, but only when those experiences involved explicit instructions, guidance, and closure. On the other hand, students they characterized as *sociable* displayed a distinct preference for group discussions. Other students whom they characterized as *achievers* preferred more individualized or whole class instructional situations. These relationships and other findings suggested the importance of rethinking and reshaping the work of students in the science laboratory to engage students in ways consistent with their diverse experiences, knowledge, and cognitive preferences, perhaps through small group collaboration and inquiry or occasionally through independent inquiry. This suggestion is highly consistent with Teaching Standard 'A' (NRC, 1996, p. 30):

> Teachers of science plan an inquiry-based science program for their students. In doing this, teachers: ... select science content and adapt and design curricula to meet the interests,

> knowledge, understanding, abilities, and experiences of students . . . and work together as colleagues within and across disciplines and grade levels.

GOALS FOR LEARNING, DISCREPANCIES, AND MATCHING GOALS WITH PRACTICE

Goals

In the 1982 review, we wrote that laboratory activities offer important experiences in learning science that are unavailable in other school disciplines. For well over a century, laboratory experiences have been purported to promote key science education goals including the enhancement of students':

- Understanding of scientific concepts
- Interest and motivation
- Scientific practical skills and problem solving abilities
- Scientific habits of mind (more recent)
- Understanding of the nature of science (more recent)

In 1983, the National Commission on Excellence in Education (1983) published *A Nation at Risk: The Imperative for Educational Reform*. This frequently cited report (in the 1980s and 90s) offered recommendations for schooling in the United States that promoted the movement toward National Standards. Recommendations included those noted above and emphasized that high school science should provide graduates with experiences in

- methods of scientific inquiry and reasoning and
- application of scientific knowledge to everyday life.

Often the goals articulated for learning in the laboratory have been almost synonymous with those articulated for learning science more generally. Hodson (2001) claimed that in the past 30 years the motives for laboratory/practical work have remained unchanged although relative priorities may have shifted somewhat (see also Gayford, 1988; Hegarty-Hazel, 1990; Tamir, 1990).

To guide teaching and learning, it is very important for both teachers and students to be explicit about the general and specific purposes of what they are doing in the classroom. Explicating goals for specific *students' learning* outcomes should serve as a principal basis upon which teachers design, select, and use activities; the goals can also serve as the most important bases for assessment of students and of the curriculum and teaching strategies. To these ends, it is important to acquire information and insight about what is really happening when students engage in laboratory activities, i.e., we need to examine what the students are perceiving in the light of important goals for science learning.

Students' Perceptions of Teachers' Goals

Chang and Lederman (1994) and others (e.g. Wilkenson & Ward, 1997) have found that often students do not have clear ideas about the general or specific purposes for their work in science laboratory activities. Other studies have shown that students often perceive that the principal purpose for a laboratory investigation is either *following the instructions* or *getting the right answer*. They may perceive that manipulating equipment and measuring are goals but fail to perceive much more important conceptual or even procedural goals.

Students often fail to understand and to question the relationship between the purpose of their investigation and the design of the experiment they have conducted, they do not connect the experiment with what they have done earlier, and they seldom note the discrepancies between their own concepts, the concepts of their peers, and those of the science community (see for example, Champagne, Gunstone, & Klopfer, 1985; Eylon & Linn, 1988). To many students, "a lab" means manipulating equipment but not manipulating ideas.

Mismatches often occur between teachers' perceived goals for practical work and students' perceptions of such activities (Hodson, 1993, 2001; Wilkenson & Ward, 1997). Since there is evidence that the goals of instruction are more likely to be achieved when students understand those goals, Wilkenson and Ward concluded that teachers should be much more attentive to helping students understand the general goals of the laboratory work. Since specific objectives are often different from one laboratory investigation to another, students should be helped to understand the purposes for each investigation in a prelab session and to review those purposes in postlab reporting and discussion. To complicate matters further, Hodson (2001) observed that often teachers do not do in laboratories what they say they intend to do. Thus, there can also be a mismatch between a teacher's rhetoric and classroom behavior that can send mixed messages to students and other observers.

Teachers' Expectations and Behavior

Tobin and Gallagher (1987) found that science teachers rarely, if ever, exhibit behavior that encourages students to think about the nature of scientific inquiry and the meaning and purposes for their particular investigation during laboratory activities. On the basis of a comprehensive study on implementation of the laboratory in schools in British Columbia, Gardiner and Farrangher (1997) found that although many biology teachers' articulated philosophies appeared to support an investigative, hands-on, minds-on approach with authentic learning experiences, the classroom practice of those teachers did not generally appear to be consistent with their stated philosophies. As noted in the preceding section, Hodson's observations of the mismatch between teacher's rhetoric and practice, also complicates obtaining valid and reliable information based only upon teachers' self-reports. Several studies have reported that very often teachers involved students principally in relatively low-level, routine activities in laboratories and that teacher–student interactions focused principally on low-level procedural questions and answers. Marx et al. (1998) reported that science teachers often have difficulty helping students ask thoughtful questions, design investigations, and draw conclusions from data. DeCarlo and Rubba (1994) reported similar findings in chemistry laboratory settings.

Earlier, Shymansky and Penick (1978) had written

> Teachers are often confused about their role in instruction when students are engaged in hands-on activity. Many teachers are concerned about an adjustment they may have to make in their teaching style to facilitate hands-on programs as well as how students will react to increased responsibility and freedom.

Often teachers do not perceive that laboratory activities can serve as a principal means of enabling students to construct meaningful knowledge of science, and they do not engage students in lab activities in ways that are likely to promote the development of science concepts. They may not perceive that they can manage lab activities in ways that are consistent with contemporary professional standards. In addition, many teachers do not perceive that helping students understand how scientific knowledge is developed and used in a scientific community is an especially important goal of laboratory activities for their students.

As noted in other sections of this review, several researchers have continued to observe that many science teachers do not utilize or manage the unique environment of the school laboratory effectively. Conditions are especially demanding in science laboratories in which the teacher is to act as a facilitator who guides inquiry that enables students to construct more scientific concepts. Contemporary teaching standards place a heavy burden on the science teacher. Inquiry-focused teaching now rests on the constructivist notion that learning is a process in which the student actively constructs her or his own ideas that are linked with other ideas in increasingly complex networks. The constructivist model, when practiced, is a relatively radical departure from traditional teaching and learning practice. Teachers are often not well informed about these new models of learning (Cohen, 1990; Polman, 1999) and their implications for classroom teaching and curriculum. While excellent examples of teaching can be observed, the classroom behaviors of many teachers continue to suggest the conventional belief that knowledge is directly transmitted to good students and that it is to be remembered as conveyed.

In addition, many teachers lack experience with assessment methods aimed at assessing their students' understanding and performance in the science laboratory (Yung, 2001). As a result, in many cases, students' final grades do not include a component that directly reflects their performance in laboratory work and their understanding of that work. Furthermore, Brickhouse and Bodner (1992) reported that students' concerns about their grades has a strong influence on teachers' practices. More specifically, they suggested that some teachers will emphasize goals for learning and use teaching techniques that are aligned with students' ability to earn high grades.

The need for meaningful, long-term professional development for science teachers on these issues and for better communication between the science education research community and the community of science teachers is abundantly clear. These important issue are discussed further in the Teacher Education and Professional Development section later in this review.

The Laboratory Guide

In most school laboratory activities, the student's laboratory guide, handbook, or worksheet, sometimes delivered in electronic form, continues to play a central role in shaping the students' behaviors and learning. The guide focuses students' attention on the questions to be investigated and on what is to be done, observed, interpreted, and reported. It plays a major role in defining goals and procedures. Lunetta and Tamir (1979) developed a set of protocols for analyzing student laboratory activities, which they used in the 1980s to analyze several secondary school science laboratory programs systematically. Similar protocols were used more recently in Australia by Fisher et al. (1999). The analyses continue to suggest that to date, many students engage in laboratory activities in which they follow recipes and gather and record data without a clear sense of the purposes and procedures of their investigation and their interconnections. In addition, the quantity of information presented in the laboratory guide is often so substantial, according to Johnstone and Wham (1982), that the details can distract the learner from the main goals of the practical task. Consistent with the findings of Lunetta and Tamir (1979) and others, students are seldom given opportunities to use higher-level cognitive skills or to discuss substantive scientific knowledge associated with the investigation, and many of the tasks presented to them continue to follow a "cookbook" approach (Roth, 1994).

Our 1982 review also reported that there were vast differences in the learning strategies implicit in different laboratory guides that were bound to influence students' learning. The nature of the instructions and especially of the evaluation shapes the expectations, purpose, and behaviors of the students in laboratory activities. Gathering and analyzing such information is a very important element of research in the laboratory that should be included in research reports. At this writing, the recommendations of science education standards and reform documents appear to have had only marginal influence on the development and publication of laboratory guides, practical assessment, and on the school laboratory practices that follow. In fact, the almost simultaneous emphasis on *conventional* paper and pencil assessment (not performance assessment) has almost certainly had a negative effect (Bryce & Robertson, 1985; Lazarowitz & Tamir, 1994). Nevertheless, there are some noteworthy exceptions such as the resources developed and implemented in the Learning through Collaborative Visualization project and the Detroit urban science initiative project and reported by Fishman et al. (2001), Polman (1999), and others. These projects have developed curriculum and teaching strategies that incorporate constructivist pedagogy enhanced by appropriate computer and communication technology tools; they have also incorporated formative and summative research to inform and assess development and teaching in the projects.

Incorporating Inquiry Empowering Technologies

"Inquiry empowering technologies" can assist students in gathering, organizing, visualizing, and interpreting data. Students can use probes to gather many data points rapidly. They can also use new technology tools to gather data across multiple trials and across long time intervals (Friedler, Nachmias, & Linn, 1990; Krajcik et al., 2000; Dori & Barak, 2001; Lunetta, 1998). By using associated software they can examine graphs of relationships generated in real time as the investigation progresses, and examine the same data in spreadsheets and in other visual representations. When inquiry empowering technologies are properly used by teachers and students to gather and analyze data, students have more time to observe, to reflect, and to construct conceptual knowledge that underlies the laboratory experiences. In addition, the associated graphics offer visualization that can enhance students' understanding. When students have the time, and when the activity is valued by the instructor (and by the evaluation system), they can examine functional relationships and the effects of modifying variables; they can also make and test predictions and explanations. Such experiences also offer opportunities that may help students to perceive a more complete inquiry process rather than discrete, perhaps disconnected, segments of the process. Furthermore, incorporating appropriate high technology tools can enable students to conduct, interpret, and report more complete, accurate, and interesting investigations. Such tools can provide a medium for communication, for student–student collaboration, and for the development of a community of learners in the laboratory-classroom and beyond.

Zembal-Saul et al. (2002) reported that "while engaging in an original science investigation *Progress Portfolio* [software] assisted prospective teachers in developing elaborated explanations that were grounded in evidence and . . . [in exploring] alternative hypotheses." The *Progress Portfolio* (Loh et al., in press) software was designed "to promote reflective inquiry during learning in data-rich environments. Inquiry empowering software can also "provide scaffolding to support scientific practice and can be integral in new inquiry practices" (Reiser, Tabak, & Sandoval, 2001). These tools can also assist students in supporting assertions they are making about explanations and about relationships among variables with data-based evidence. As mentioned earlier, using such tools, prompted "learners to articulate and connect their experimental findings back to the larger driving questions" and to negotiate and struggle with explaining the significance of their data. It also prompted reflective social discourse that resulted in explanation and justification (Land & Zembal-Saul, in press).

During the past 20 years there have been many optimistic claims about the potential of technology tools to enhance learning, but only a limited amount of objective information has been gathered to this date regarding the effectiveness of these technologies on important learning outcomes. This domain of research is a very important area for scholarly study needed to shape the development of state-of-the-art technology tools and teaching strategies that can facilitate more meaningful and holistic science learning.

Simulation and the Laboratory

Lunetta and Hofstein (1991) noted that interacting with instructional simulations can help students understand a real system, process, or phenomenon. They suggested that within school settings, both practical activities and instructional simulations can enable students to confront and resolve problems, to make decisions, and to observe the effects. Whereas laboratory activities are designed to engage students directly with materials and phenomena, simulations can be designed to provide meaningful representations of inquiry experiences that are often not possible with real materials in many science topics. In such cases, simulations engage students in investigations that are too long or too slow, too dangerous, too expensive, or too time or material consuming to conduct in school laboratories. Research findings on effective ways to use simulations are far from conclusive. However, it is well established, in general, that engaging students in appropriate simulations takes considerably less time than engaging them in equivalent laboratory activities with materials. Until carefully conducted research provides further information, it is reasonable to assume that teaching and learning practices that have been shown to be effective in promoting more effective laboratory experiences will also tend to be appropriate for students who are exploring simulations.

We observe that some school administrators and teachers make decisions to use simulations with students instead of hands-on practical experiences (such as dissections) because the simulations are thought to be less troublesome or less expensive. Other teachers may elect to use simulations in lieu of dissections to avoid “wasting life,” or they may let students and their parents decide on the basis of their religious or moral views. It is probable that the learning that will result from engaging in a well-conducted dissection or other practical experience will be quite different from the learning that will result from a good simulation. While resources and ethical and cultural issues and resources are important elements in the school/community environment, decisions about when to have students work with simulations instead of equivalent activities in the laboratory should be made principally on the basis of the intended learning outcomes and informed by research on learning and the positions of appropriate professional societies. The intersections of laboratory activities and simulations warrants special attention by science educators at this nascent and important time in the development of new simulation technologies appropriate for school science.

Assessing Students’ Skills and Understanding of Inquiry

In the 1982 review, we criticized much of the research on the laboratory because it failed to assess learning outcomes that one might assume would be developed and enhanced in laboratory activities. Assessments of students’ performance and understanding associated with the science laboratory should be an integral part of the laboratory work of teachers and students. Assessment tools should examine the students’ inquiry skills, their perceptions of scientific inquiry, and related scientific concepts and applications identified as important learning outcomes for the investigation or the series of investigations. Since 1982, knowledge about how to assess learning in the school science laboratory has increased substantially, and new techniques and media that can support the assessment of students' practical skills and associated understanding have been developed. In Israel, for example, Tamir, Nussinovitz, and Friedler (1982) developed a standardized practical test in biology that includes 21 assessment categories. Each year novel "experiments" are developed for that Israeli test, and the students' performance is assessed using the 21 categories. In the United States, Doran et al. (1993) developed and validated a test to assess the laboratory skills of students completing high school science courses (chemistry, biology, and physics). Their aim was to develop an authentic and alternative assessment method to measure outcomes of school science programs, including inquiry and activity in the laboratory. In their tests, students had to design an investigation, collect and analyze data, and formulate findings. The students' visual representation and interpretation of their quantitative data was incorporated in the analysis.

Several observational assessment methods were developed in the 1970s and 1980s (e.g., Eglen & Kempa, 1974; Ganiel & Hofstein, 1982; Hofstein et al., 2001; Tamir, 1972). Using certain criteria, the researchers or teachers unobtrusively observe and rate each student during normal laboratory activities. They assess students according to the following broad phases of activity: (1) planning and design, (2) performance, (3) analysis and interpretation, and (4) application. (For a more detailed description of the assessment methods, see, Giddings, Hofstein, & Lunetta, 1991; Hofstein, 1988; Lunetta & Tamir, 1979.)

Recent developments in the use of new technology tools that are now beginning to be used in science classrooms have high potential to help researchers and even busy teachers to monitor students' work and ideas. *Progress Portfolio* (Loh et al., in press) software, referenced in the *Inquiry Empowering Technologies* section earlier in this paper, is one example of software used by students that can provide teachers with relatively easy electronic access to student performance data to be included in assessing a student's development and progress. Teachers can also use that kind of information as formative assessment to inform their teaching and their interactions with students.

The new practical assessment resources and strategies can be used by researchers and busy teachers to assess learning associated with inquiry and laboratory performance. Development and use of assessment resources is also a very important area for further discipline-focused research in science education. Such research could also serve as a foundation for developing assessment protocols for teachers to use effectively in their own classrooms without expending large quantities of their very limited time. In addition, such assessment protocols should provide feedback for teachers to improve the effectiveness of their own teaching. That feedback, of course, could also be used to help students understand how they are progressing as learners. Gitomer and Duschl (1998, p. 803), wrote:

> The most promising efforts in assessment reform are those that address directly the relationship of assessment and instruction, specifying precisely how assessment can be used to support improved instructional practice.

If we truly value the development of knowledge, skills, and attitudes that are unique to practical work in science laboratories, appropriate assessment of these outcomes must be developed and implemented continuously by teachers in their own laboratory-classrooms. The *National Science Education Standards* (NRC, 1996) indicates that all the student's learning experiences should be assessed and that the assessment should be authentic. Attention to such *standards*, however, has promoted testing that has generally not incorporated the assessment of performance and inquiry, although there have been a few noteworthy efforts to do that. Researchers, teachers, and testing jurisdictions whose goal is to assess comprehensively the learning that takes place in school science generally, or in school laboratories more specifically, should use appropriate assessment tools and methodologies to identify what the students are learning (conceptual as well as procedural). The effects of such experiences on students' interest and motivation should also be assessed.

In summary, data gathered in many countries has continued to suggest that teachers spend large portions of laboratory time in managerial functions, not in soliciting and probing ideas or in teaching that challenges students' ideas, encouraging them to consider and test alternative hypotheses and explanations. In addition, most of the assessment of students' performance in the science laboratory continues to be confined to conventional, usually objective, paper and pencil measures. More sensitive measures of students' understanding of laboratory methodologies, the hypotheses and questions they generate from the lab experiences, and the practical skills they exhibit have all too often been neglected (Bryce & Robertson, 1985; Hofstein, Shore, & Kipnis, in press; Tamir, 1989; Van den Berg & Giddings, 1992; Wilkenson & Ward, 1997). In this era when standards and external tests of students' achievement are increasingly popular, it is naïve to think that students' and teachers' behavior and practices will shift toward inquiry and the development of meaningful practical knowledge until such outcomes become more visible in the tests that increasingly drive what teachers, parents, and students think is important, and thus what they choose to do. The policy makers who control the testing programs and those who prepare the tests must be part of more functional efforts to improve the effectiveness of school science.

The Politics of Schooling

In the United States, and in many other countries, scientists in higher (tertiary level) education have been very influential in the design and implementation of science curricula (Fensham, 1992, 1993). Yet, studies of freshman level university courses in the natural sciences showed that these courses had changed only slightly in style from university courses offered in the 1960s. Furthermore, teaching in university level courses has a powerful influence on the education, socialization, and subsequent behavior of science teachers at secondary and elementary school levels. Fensham claimed that the dominant perception of university science faculty members has been that the principal goal of secondary school science education is to prepare students for success in the university level science. "Thus, the content and knowledge of worth for senior secondary sciences is to be determined by the knowledge and expression of it that is now well established as the content of freshman science courses in chemistry, biology and physics" (pp. 61–62). He wrote that the attitude of many university scientists toward the science curriculum inhibited the implementation of many of the new science education goals, strategies, and foci such as *science for all*, *inquiry*, *applications*, and *science–technology–society*. In addition, competent secondary science teachers have had limited voice and power to shape curriculum and policy decisions in school science. Policy decisions are often made at state (or in the United States at district) levels where people with expertise in science teaching have had very limited voice.

TEACHER EDUCATION AND PROFESSIONAL DEVELOPMENT

The school science laboratory continues to be perceived as a unique environment for teaching and learning science in a social setting that includes interactions with materials and data, interactions between and among students, their teacher, and sources of "expert" information. Nevertheless, as noted throughout this review, researchers have continued to observe that many science teachers do not utilize or manage this unique environment effectively. In the section entitled *Teachers' Expectations and Behavior*, we noted that

> *conditions are especially demanding in science laboratories in which the teacher is to act as a facilitator who guides inquiry that enables students to construct more scientific concepts. . . . Teachers are often not well informed about new models of learning and their implications for teaching and curriculum. While excellent examples of teaching can be observed, the classroom behaviors of many teachers continues to suggest the conventional belief that knowledge is directly transmitted to good students and that it is to be remembered as conveyed.*

That said, many preservice and in-service courses in science and in science teaching and learning provide very limited direct experience, if any, through which the teachers can develop the skills needed to organize and facilitate meaningful, practical learning experiences for students in the school science laboratory (Tamir, 1989). Tamir wrote that policy makers often assume that participating in science laboratory work in university courses during their preparation provides them with knowledge and skills sufficient to teach successfully in school science laboratories. While that assumption appears to be widely held, it is not consistent with a growing array of formal and informal data on teachers' conceptual and pedagogical knowledge and teaching practices (Loucks-Horseley & Matsumoto, 1999). Yung (2001) and others, for example, reported that many teachers lack experience with methods enabling them to assess their students' understanding and performance in the science laboratory. Thus, students' grades often do not reflect their performance in the laboratory work or their understanding of that work.

Appropriate long-term professional development has been suggested increasingly as one of the important ways to help teachers develop professional understandings, beliefs, roles, and behaviors (Tobin, 1990). This can be accomplished, in part, by implementing the science teachers' professional development standards that are central elements within the *National Science Education Standards* (NRC, 1996). Long-term and continuous professional development aimed at enhancing science teachers' content knowledge and their pedagogical content knowledge (Gess-Newsome, 1999; Shulman, 1986) can help teachers develop higher levels of pedagogical and content knowledge, skills, and confidence to construct effective learning environments that include substantive and meaningful science laboratory experiences. In this era of exponentially expanding knowledge of science and pedagogy, such development should be a continuous process across the professional lifetime of a teacher. The literature has suggested that inconsistencies between teachers' goals and behaviors and limitations in teachers' skills, in this case in the school laboratory, should be addressed carefully in long-term professional development programs designed to develop the understanding, knowledge, and skill of professional teachers.

Strategies to be included in professional development include those described by Loucks-Horsley et al. (1998) as *action research* in which teachers examine the nature and effects of their own teaching. This can include investigating the effectiveness of certain teaching strategies or curriculum modifications. In the latter, teachers adapt and tailor a certain learning unit to match the abilities and needs of their students, a process labled as *curriculum development and adaptation* (Loucks-Horsley et al., 1998). These strategies for professional development are teacher-based and informed by relevant scholarship. The teaching strategies and curriculum material are developed and assessed by teachers with the support and guidance of consultants from academic institutions or curriculum-development centers. Good professional development can increase each teacher's ownership of specific instructional approaches and learning units. In addition, it can promote the idea that professional teachers are responsible for the progress of the students in their classes. Kennedy (1998) wrote that when teachers undergo learning experiences that engage them in meaningful inquiry, they can become more effective in involving their own students in similar inquiry experiences. The power of placing lead teachers in central roles in the development of curriculum materials and teaching strategies is also very visible in the series of research and development projects conducted by Krajcik et al. (2000) and Fishman et al. (2001) in the city of Detroit and in other sites. The visible success of that series of projects in promoting inquiry, meaningful practical activities, and student use of new technology tools in difficult urban school environments is especially noteworthy. Unfortunately, however, at present there are very few projects of this kind, magnitude, and commitment.

As noted throughout this paper, the need for meaningful, long-term professional development for science teachers on these and many related issues in science education and the need for better communication between the science education research community and the community of science teachers has become abundantly clear. Greater interaction has been inhibited, in part, by contemporary institutional structures that separate science teachers from the scientific community, from the science education research community, from meaningful professional development in science and in science pedagogy, and from participating in policy making as competent professionals. Reducing the institutional and cultural barriers that inhibit communication between these several science education communities and developing appropriate professional development and engagement systems is a very important task for policy makers and for members of those communities. To these ends, policy makers, teacher associations, departments of education, and schools need to collaborate and to set aside sufficient time and resources to enable that professional growth and empowerment guided by school realities and by relevant scholarship to occur. Policy changes, implementation, and careful research on the process are needed to achieve the very important ends that have been articulated.

WHERE WE ARE IN 2002: IMPLICATIONS FOR THE TWENTY-FIRST CENTURY

In summarizing the 1982 review of research on laboratory work, we wrote (p. 213)

> Researchers must examine the goals of science teaching and learning with care to identify optimal activities and experiences from all modes of instruction that will best facilitate these goals. . . . There is a real need to pursue vigorously research on learning through laboratory activities to capitalize on the uniqueness of this mode of instruction for certain learning outcomes.

While there is little doubt that substantial progress has been made in identifying teacher behaviors and other variables that can promote meaningful learning consistent with contemporary standards, these comments are also valid at this writing 20 years later. That said, the assumption that laboratory experiences help students understand materials, phenomena, concepts, models, and relationships, almost independent of the nature of the laboratory experience, continues to be widespread in spite of sparse data from carefully designed and conducted studies. A more recent assertion is that laboratory experiences can help students develop ideas about the nature of a scientific community and the nature of science. During the past 20 years substantial new knowledge has been developed about cognitive development, the learning of science, and the nature of science. This new knowledge has fueled many ideas about ways the introductory sciences should be taught to promote understanding. In addition, significant changes in computer technologies offer substantive new tools and resources for empowering teaching and learning science that can complement experiences in the school laboratory. Moreover, more sensitive social science research methodologies have been developed that enable science education researchers to examine more carefully the ideas of students and their teachers and the effects of a variety of learning environment variables on the development of students' concepts, skills, motivation, and attitudes.

There is no doubt that in the 20 years since the publication of the 1982 review (Hofstein & Lunetta, 1982), there has been substantive growth in understanding associated with teaching, learning, and assessment in the school science laboratory work. At the beginning of the 21st century, when many are again seeking reform in science education, the knowledge that has been developed about learning based upon careful scholarship should be incorporated in that reform. The "*less is more*" slogan in *Benchmarks for Science Literacy* (AAAS, 1993, p. 320) has been articulated to guide curriculum development and teaching consistent with the contemporary reform. The intended message is that formal teaching results in greater understanding when students study a limited number of topics, in depth and with care, rather than a large numbers of topics much more superficially, as is the practice in many science classrooms. Well-designed science laboratory activities focused on inquiry can provide learning opportunities that help students develop concepts and frameworks of concepts. They also provide important opportunities to help students learn to investigate, to construct *scientific* assertions, and to justify those assertions in a classroom community of peer investigators in contact with a more expert scientific community. To attain such important but demanding goals, the education system must provide time and opportunity for teachers to interact with their students and also time for students to perform and reflect on complex, investigative tasks.

Clearly, serious discrepancies exist between what is recommended for teaching in the laboratory-classroom and what is actually occurring in many classrooms. Researchers need to examine and understand why large numbers of "good teachers" have not been using authentic and practical assessment on a regular basis. Such understanding should then shape research on classroom practice, the development of assessment techniques, teacher professional development, and further research studies. No doubt, the issues are complex, but explanations may lie in differences in the perceptions of teachers and researchers. For example, teachers may perceive they do not have the time or skill required to implement such assessment methodologies successfully. Reluctance may also originate in the beliefs teachers hold about what students should be learning in laboratory experiences, how students learn, what they need to do to achieve important learning outcomes, and what they need to perform successfully on external examinations. Building on relevant scholarship, future research in science education should produce information that informs the development of strategies, protocols, and resources for teaching and for the professional development of teachers. Questions to be addressed include how to assess students' learning efficiently and effectively when they are engaging in inquiry and practical work, how to engage students with different skills and knowledge in practical experiences that result in meaningful learning, and how to promote a more effective laboratory learning environment.

During the past 20 years, we have expanded our knowledge about circumstances that inhibit and promote conceptual learning in science classrooms and in the science laboratory. Factors that continue to inhibit learning in the school science laboratory include the following:

- Many of the activities outlined for students in laboratory guides continue to offer "cook-book" lists of tasks for students to follow ritualistically. They do not engage students in thinking about the larger purposes of their investigation and of the sequence of tasks they need to pursue to achieve those ends.
- Assessment of students' practical knowledge and abilities and of the purposes of laboratory inquiry tends to be seriously neglected, even by high stakes tests that

purport to assess science standards. Thus many students do not perceive laboratory experiences to be particularly important in their learning.
- Teachers and school administrators are often not well informed about what is suggested as best professional practice, and they do not understand the rationale behind such suggestions. Thus, there is a high potential for mismatch between a teacher's rhetoric and practice that is likely to influence students' perceptions and behaviors in laboratory work.
- Incorporating inquiry-type activities in school science is inhibited by limitations in resources (including access to appropriate technology tools) and by lack of sufficient time for teachers to become informed and to develop and implement appropriate science curricula. Other inhibiting factors include large classes, inflexible scheduling of laboratory facilities, and the perceived foci of external examinations.

The nature and the sources of these problems need to be examined carefully and recommendations for policy and practice need to be based upon the findings of that research.

There are important opportunities to pursue research and development building on what we know and on the scholarship of the past in order to enhance the effectiveness of science education. Special opportunities identified in this review include developing and assessing teaching strategies, assessment tools, and resources that are effective in helping teachers and students to attain important learning goals that

- engage students with different abilities, learning styles, motivational patterns, and cultural contexts;
- engage students in using inquiry empowering tools and strategies; and
- engage students in justifying assertions on the basis of scientific evidence.

More particularly, this review of the scholarly literature in science education suggests the following implications:

- Goals for students' learning outcomes must drive what is done by curriculum developers and by teachers in the classroom and the laboratory.
- Effective teaching engages, builds upon, and enhances students' knowledge (conceptual and procedural), attitudes, perceptions, culture, etc.
- Local and external assessment of students' learning and attitudes must be consistent with the goals for learning outcomes.
- Classroom-based research and development associated with curriculum and teaching is important in helping science teachers and students achieve important science learning outcomes.
- Appropriate teacher professional development, informed by relevant scholarship, is important in helping teachers to become more effective in science teaching.

In a time of increasingly rapid change in science and technology, competent teachers must continue to be informed about contemporary professional issues across a professional lifetime. Developing appropriate institutional structures that enable and promote such professional development is a very important task that needs attention, not only by teachers and their professional associations but by education policy makers at every level of school administration and government.

Finally, it is disappointing to note the continuing limitations in systematic scholarship associated with such a central medium as the laboratory in science education. There is new information about limitations in the effectiveness of school science education; there also continue to be important reasons to believe that

- school laboratory activities have special potential as media for learning that can promote important science learning outcomes for students;
- teachers need knowledge, skills, and resources that enable them to teach effectively in practical learning environments. They need to be able to enable students to interact *intellectually* as well as *physically*, involving hands-on investigation and minds-on reflection;
- students' perceptions and behaviors in the science laboratory are greatly influenced by teachers' expectations and assessment practices and by the orientation of the associated laboratory guide, worksheets, and electronic media; and
- teachers need ways to find out what their students are thinking and learning in the science laboratory and classroom.

New, more appropriate research methodologies and technology resources are now available to support research on how to help students and teachers attain the goals for science learning that data show have been difficult to achieve. In addition, it is important to provide support for teachers (including time and opportunities) to collaborate with colleagues in the science education research community so as to understand, develop, and teach in ways that are consistent with contemporary professional standards. Competent professional teachers have important roles to play in the continual renewal and development of science education standards and in supporting and doing related classroom-based research that can shape science-teaching practices. Empowering professional teachers in these roles and encouraging relevant research on central issues like supporting and assessing the effectiveness of the school science laboratory are very important next steps that warrant attention from professional societies, higher education, school administrators, and teacher certification bodies.

REFERENCES

Adar, L. (1969). A theoretical framework for the study of motivation in education. Jerusalem: The Hebrew University. (In Hebrew.)

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

Baird, J. R. (1990). Metacognition, purposeful enquiry and conceptual change. In E. Hegarty-Hazel (Ed.), The student laboratory and the science curriculum (pp. 183–200). London: Routledge.

Barron, B. J. S., Schwartz, D. L., Vye, N. J., Moore, A., Petrosino, A., Zech, L., & Bransford, D. J. (1998). Doing with understanding: Lessons from research on problem and project-based learning. The Journal of the Learning Sciences, 7, 271–311.

Bates, G. R. (1978). The role of the laboratory in secondary school science programs. In M. B. Rowe (Ed.), What research says to the science teacher (Vol. 1). Washington, DC: National Science Teachers Association.

Blosser, P. (1983). The role of the laboratory in science teaching. School Science and Mathematics, 83, 165–169.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). How people learn: Brain, mind, experience, and school. Washington, DC: National Academy Press.

Brickhouse, N., & Bodner, G. M. (1992). The beginning science teacher: Classroom narratives of convictions and constraints. Journal of Research in Science Teaching, 29, 471–485.

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. Educational Researcher, 18, 32–41.

Bryce, T. G. K., & Robertson, I. J. (1985). What can they do? A review of practical assessment in science. Studies in Science Education, 12, 1–24.

Bybee, R. (2000). Teaching science as inquiry. In J. Minstrel & E. H. Van Zee (Eds.), Inquiring into inquiry learning and teaching in science (pp. 20–46). Wasington, DC: American Association for the Advancement of Science (AAAS).

Champagne, A. B., Gunstone, R. F., & Klopfer, L. E. (1985). Instructional consequences of students' knowledge about physical phenomena. In L. H. T. West & A. L. Pines (Eds.), Cognitive structure and conceptual change (pp. 61–68). New York: Academic Press.

Chang, H. P., & Lederman, N. G. (1994). The effect of levels of cooperation with physical science laboratory groups on physical science achievement. Journal of Research in Science Teaching, 32, 167–181.

Cohen, D. K. (1990). A revolution in one classroom: The case of Mrs. Oublier. Educational Evaluation and Policy Analysis, 64, 1–35.

DeCarlo, C. L., & Rubba, P. (1994). What happens during high school chemistry laboratory sessions? A descriptive case study of the behaviors exhibited by three teachers and their students. Journal of Science Teacher Education, 5, 37–47.

Doran, R. L., Boorman, J., Chan, F., & Hejaily, N. (1993). Alternative assessment of high school laboratory skills. Journal of Research in Science Teaching, 30, 1121–1131.

Dori, Y. J., & Barak, M. (2001). Virtual & physical molecular modeling: Fostering model perception and spatial understanding. Educational Technology & Society, 4(1), 61–74.

Dreyfus, A. (1986). Manipulating and diversifying the levels of difficulty and task sophistication of one and the same laboratory exercise. European Journal of Science Education, 8, 17–26.

Driver, R. (1995). Constructivist approaches to science teaching. In L. P. Steffe & J. Gale (Eds.), Constructivism in education (pp. 385–400). Hillsdale, NJ: Lawrence Erlbaum.

Driver, R., Newton, P., & Osborne, J. (2000). Establishing the norms of scientific argumentation in classrooms. Science Education, 84(3), 287–312.

Dupin, J. J., & Joshua, S. (1987). Analogies and 'modeling analogies' in teaching: Some examples in basic electricity. Science Education, 73(2), 791–806.

Eglen, J. R., & Kempa, R. F. (1974). Assessing manipulative skills in practical chemistry. School Science Review, 56, 737–740.

Eylon, B., & Linn, M. C. (1988). Learning and instruction: An examination of four research perspectives in science education. Review of Educational Research, 58(3), 251–301.

Fensham, P. J. (1992). Science and technology. In P. W. Jackson (Ed.), Handbook of research on curriculum (pp. 789–829). New York: Maxwell Macmillan International.

Fensham, P. J. (1993). Academic influence on school science curricula. Journal of Curriculum Studies, 25, 53–64.

Fisher, D., Harrison, A., Henderson, D., & Hofstein, A. (1999). Laboratory learning environments and practical tasks in senior secondary science classes. Research in Science Education, 28, 353–363.

Fishman, B., Soloway, E., Krajcik, J., Marx, R., & Blumenfeld, P. (2001). Creating scalable and sustainable technology innovations for urban education. Paper presented at the Annual Meeting of the American Educational Meeting Association, Seattle, WA. (Available at http://hi-ce.eecs.umich.edu/index.html.)

Fraser, B., & McRobbie, C. J. (1995). Science laboratory classroom environments at schools and universities: A cross-national study. Educational Research and Evaluation, 1, 289–317.

Fraser, B., McRobbie, C. J., & Giddings, G. J. (1993). Development and cross-national validation of a laboratory classroom instrument for senior high school students. Science Education, 77, 1–24.

Friedler, Y., Nachmias, R., & Linn, M. C. (1990). Learning scientific reasoning skills in microcomputer based laboratories. Journal of Research in Science Teaching, 27, 173–191.

Ganiel, U., & Hofstein, A. (1982). Objective and continues assessment of student performance in the physics laboratory. Science Education, 66, 581–591.

Gardiner, P. G., & Farrangher, P. (1997). The quantity and quality of biology laboratory work in British Columbia high schools. Paper presented at the National Association for Research in Science Teaching (NARST) Meeting, Oak Brook, IL.

Gayford, C. (1988). Aims, purposes and emphasis in practical biology at advanced level: A study of teachers' attitudes. School Science Review, 69, 175–186.

Gess-Newsome, J. (1999). Pedagogical content knowledge an introduction and orientation. In J. Gess-Newsome & N. G. Lederman (Eds.), Examining pedagogical content knowledge (pp. 3–20). Dordrecht: Kluwer.

Giddings, G. J., Hofstein, A., & Lunetta, V. N. (1991). Assessment and evaluation in the science laboratory. In B. E. Woolnough (Ed.), Practical science (pp. 167–178). Milton Keynes: Open University Press.

Gitomer, D. H., & Duschl, R. A. (1998). Emerging issues and practices in science assessment. In B. J. Fraser & K. G. Tobin (Eds.), International handbook of science education (pp. 791–810). Dordrecht: Kluwer.

Gunstone, R. F. (1991). Reconstructing theory from practical experience. In B. E. Woolnough (Ed.), Practical science (pp. 67–77). Milton Keynes: Open University Press.

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

Harms, N., & Yager, R. E. (1981). What Research Says to the Science Teacher (Vol. II). Washington, DC: National Science Teachers Association.

Hegarty-Hazel, E. (1990). The student laboratory and the science curriculum: An overview. In E. Hegarty-Hazel (Ed.), The student laboratory and the science curriculum (pp. 3–26). London: Routledge.

Hodson, D. (1993). Re-thinking old ways: Towards a more critical approach to practical work in school science. Studies in Science Education, 22, 85–142.

Hodson, D. (2001). Research on practical work in school and universities: In pursuit of better questions and better methods. Proceedings of the 6th European Conference on Research in Chemical Education, University of Aveiro, Aviero, Portugal.

Hofstein, A. (1988). Practical work and science education. In P. Fensham (Ed.), Development and dilemmas in science education (pp. 189–217). London: Falmer Press.

Hofstein, A., Cohen, I., & Lazarowitz, R. (1996). The learning environment of high school students in chemistry and biology laboratories. Research in Science and Technological Education, 14, 103–115.

Hofstein, A., & Kempa, R. F. (1985). Motivating aspects in science education: An attempt at an analysis. European Journal of Science Education, 7, 221–229.

Hofstein, A., Levi-Nahum, T., & Shore, R. (2001). Assessment of the learning environment of inquiry-type laboratories in high school chemistry. Learning Environments Research, 4, 193–207.

Hofstein, A., & Lunetta, V. N. (1982). The role of the laboratory in science teaching: Neglected aspects of research. Review of Educational Research, 52(2), 201–217.

Hofstein, A., Shore, R., & Kipnis, M. (In press). Providing high school chemistry students with opportunities to develop learning skills in an inquiry-type laboratory—A case study. International Journal of Science Education.

Hurd, P. D. (1969). New directions in teaching secondary school science. Chicago: Rand McNally.

Hurd, P. D. (1983). Science education: The search for new vision. Educational Leadership, 41, 20–22.

Jimenez-Aleixandre, M. P., Rodriguez, A. B., & Duschl, R. A. (2000). "Doing the lesson" or "Doing science": Arguments in high school genetics. Science Education, 84(6), 757–792.

Johnson, D. W., & Johnson, R. T. (1985). Learning together and alone: Cooperative, competitive, and individualistic learning (2nd ed.), Engelwood Cliffs, NJ: Prentice Hall.

Johnson, D. W., Johnson, R. T., Maruyama, G., Nelson, D., & Skon, L. (1981). Effects of cooperative, competitive, and individualistic goal structures on achievement: A meta analysis. Psychological Bulletin, 89, 55–63.

Johnstone, A. H., & Wham, A. J. B. (May 1982). The demands of practical work. Education in Chemistry, 71–73.

Karplus, R. (1977). Science teaching and the development of reasoning. Journal of Research in Science Teaching, 14, 169–175.

Kempa, R. F., & Diaz, M. (1990). Motivational traits and preferences for different instructional modes in science. International Journal of Science Education, 12, 195–203.

Kennedy, M. M. (1998). The relevance of content in in-service teacher education. Paper Presented at the Annual Meeting AERA, San Diego, CA.

Krajcik, J., Blumenfeld, B., Marx, R., & Soloway, E. (2000). Instructional, curricular, and technological supports for inquiry in science classrooms. In J. Minstrell & E. Van Zee (Eds.), Inquiring into inquiry: Science learning and teaching (pp. 283–315). Washington, DC: American Association for the Advancement of Science Press.

Krajcik, J., Mamlok, R., & Hug, B. (2001). Modern content and the enterprise of science: Science education in the twentieth century. In L. Corno (Ed.), Education across a century: The centennial volume (pp. 205–238). Chicago: University of Chicago Press. 100th Yearbook of the National Society for the Study of Education.

Kyle, W. C. (1984). Curriculum development projects of the 1960s. In D. Holdzkom & P. B. Lutz (Eds.), Research within reach: Science education (pp. 3–24). Washington, DC: National Science Teachers Association.

Land, S., & Zembal-Saul, C. (In press). Scaffolding reflection and revision of explanations about light during project-based learning: An investigation of progress portfolio. Educational Technology Research and Development.

Lazarowitz, R., & Karsenty, G. (1990). Cooperative learning and student academic achievement, process skills, learning environment and self-esteem in 10th grade biology. In S. Sharan (Ed.), Cooperative learning, theory and research (pp. 123–149). New York: Praeger.

Lazarowitz, R., & Tamir, P. (1994). Research on using laboratory instruction in science, In D. L. Gabel (Ed.), Handbook of research on science teaching and learning (pp. 94–130). New York: Macmillan.

Loh, B., Reiser, B. J., Radinsky, J., Edelson, D. C., Gomez, L. M., & Marshall, S. (In press). Developing reflective inquiry practices: A case study of software, the teacher, and students. In K. Crowley, C. Schunn, & T. Okada (Eds.), Designing for science: Implications from everyday, classroom, and professional settings. Mahwah, NJ: Erlbaum. (Also available at http://www.ls.sesp.northwestern.edu/sible/.)

Loucks-Horsley, S., Hewson, P. W., Love, N., & Stiles, K. E. (1998). Designing professional development for teachers of science and mathematics. Thousand Oaks, CA: Corwin Press.

Loucks-Horsley, S., & Matsumoto, C. (1999). Research on professional development for teachers of mathematics and science: The state of the scene. School Science and Mathematics, 99, 258–271.

Lunetta, V. N. (1998). The school science laboratory: Historical perspectives and centers for contemporary teaching. In B. J. Fraser & K. G. Tobin (Eds.), International handbook of science education. Dordrecht: Kluwer.

Lunetta, V. N., & Hofstein, A. (1991). Simulations and laboratory practical activity. In B. E. Woolnough (Ed.), Practical science (pp. 125–137). Milton Keynes: Open University Press.

Lunetta, V. N., & Tamir, P. (1979). Matching lab activities with teaching goals. The Science Teacher, 46, 22–24.

Marx, R. W., Freeman, J. G., Krajcik, J. S., & Blumenfeld, P. C. (1998). Professional development of science teachers. In B. J. Fraser & K. G. Tobin (Eds.), International handbook of science education (pp. 667–680). Dordrecht: Kluwer.

Millar, R., & Driver, R. (1987). Beyond process. Studies in Science Education, 14, 33–62.

National Commission on Excellence in Education. (1983). A nation at risk: The imperative for educational reform (1983). Washington, DC: The National Commission on Excellence in Education.

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

National Research Council. (2000). Inquiry and the national science education standards. Washington, DC: National Academy Press.

Newton, P., Driver, R., & Osborne, J. (1999). The place of argumentation in the pedagogy of school science. International Journal of Science Education, 21(5), 553–576.

Okebukola, P. A. O., & Ogunniyi, M. B. (1984). Cooperative, competitive, and individualistic laboratory interaction patterns: effects on students' performance and acquisition of practical skills. Journal of Research in Science Teaching, 21, 875–884.

Penner, D. E., Lehrer, R., & Schauble, L. (1998). From physical models to biomechanics: A design based modeling approach. The Journal of the Learning Sciences 7, 429–449.

Polman, J. L. (1999). Designing project-based science: Connecting learners through guided inquiry. New York: Teachers College Press.

Press, M. B. (1982). The fate of school science. Science, 216, 1055.

Reiser, B. J., Tabak, I., & Sandoval, W. A. (2001). BGuILE: Strategic and conceptual scaffolds for scientific inquiry. In S. M. Carver & D. Klahr (Eds.), Cognition and instruction: Twenty-five years of progress. Mahwah, NJ: Erlbaum. (Also available at http://www.letus.org/bguile/index.html.)

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

Roth, W. M. (1995). Authentic science: Knowing and learning in open-inquiry science laboratories. Dordrecht: Kluwer.

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

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

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. Educational Researcher, 15, 4–14.

Shulman, L. D., & Tamir, P. (1973). Research on teaching the natural sciences. In R. M. W. Travers (Ed.), Second handbook of research on teaching (pp. 1098–1140). Chicago: Rand McNally.

Shymansky, J. A., Kyle, W. C., & Alport, J. M. (1983). The effects of the new science curricula on student performance. Journal of Research in Science Teaching, 20, 387–404.

Shymansky, J. E., & Penick, J. E. (1978). Teachers' behavior does make a difference in the hands-on science classroom. Paper Presented at the Annual Conference of the Association for the Education of Teachers of Science (AETS).

Tamir, P. (1972). The practical mode a distinct mode of performance. Journal of Biological Education, 6, 175–182.

Tamir, P. (1989). Training teachers to teach effectively in the laboratory. Science Education, 73, 59–69.

Tamir, P. (1990). Evaluation of student work and its role in developing policy. In E. Hegarty-Hazel (Ed.), The student laboratory and the science curriculum (pp. 242–266). London: Routledge.

Tamir, P., Nussinuvitz, R., & Fridler, Y. (1982). The design and use of practical tests assessment inventory. Journal of Biological Education, 16, 42–50.

Tobin, K. G. (1986). Student task involvement and achievement in process-oriented science activities. Science Education, 70, 61–72.

Tobin, K. G. (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. G., & Gallagher, J. J. (1987). What happens in high school science-classrooms. Journal of Curriculum Studies, 19, 549–560.

Van den Berg, E., & Giddings, G. J. (1992). Laboratory practical work: An alternative view of laboratory teaching. Perth, Australia: Curtin University of Technology.

Van den Berg, E., Katu, N., & Lunetta, V. N. (1994). The role of 'experiments' in conceptual change. Paper Presented at the Annual Meeting of the National Association for Research in Science Teaching, Anaheim, CA.

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

White, R. T., & Gunstone, R. F. (1992). Probing understanding. London: Falmer Press.

Wilkenson, J. W., & Ward, M. (1997). The purpose and perceived effectiveness of laboratory work in secondary schools. Australian Science Teachers' Journal, 43–55.

Williams, S. M., & Hmelo, C. E. (1998). Guest editors' introduction. The Journal of the Learning Sciences, 7, 265–270.

Woolnough, B. E. (1991). Setting the scene. In B. E. Woolnough (Ed.), Practical science (pp. 3–9). Milton Keynes: Open University Press.

Yager, R. E. (1984). The major crisis in science education. School Science and Mathematics, 84, 189–198.

Yung, B. H. W. (2001). Three views of fairness in a school-based assessment scheme of practical work in biology. International Journal of Science Education, 23, 985–1005.

Zeidler, D. L. (1997). The central role of fallacious thinking in science education. Science Education, 81, 483–496.

Zembal-Saul, C., Munford, D., Crawford, B., Friedrichsen, P., & Land, S. (2002). Scaffolding pre-service science teachers' evidence-based arguments during an investigation of natural selection. Research in Science Education, 32(4), 437–463.