# Learning and teaching in the school science laboratory: An analysis of research, theory, and practice

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**3 authors:**

Vincent N Lunetta
Pennsylvania State University

Avi Hofstein
Weizmann Institute of Science

Michael P Clough
Texas A&M University

# CHAPTER 15

# Learning and Teaching in the School Science Laboratory: An Analysis of Research, Theory, and Practice

**Vincent N. Lunetta**
*Pennsylvania State University*

**Avi Hofstein**
*The Weizmann Institute of Science, Israel*

**Michael P. Clough**
*Iowa State University*

Knowledge of the natural sciences is constructed to explain objects, phenomena, and their interactions in the natural world. With time, scientific ideas or concepts become connected by wider-ranging theories, and especially since the Renaissance, new knowledge and understanding has developed through continual, dynamic interaction between scientific theories, research, and experimental data. This complex interaction sometimes results in the rejection or modification of prior ideas and the development of newer ideas that link concepts together, in turn suggesting new methods, new interpretations of data, and new questions. Often, but not always, the data have come from carefully controlled studies conducted in scientists' laboratories. This kind of interrogation of nature often brings forth information that would not have been evident simply through direct observation of the natural world.

There are interesting similarities and differences between the ways that scientific communities develop new knowledge of the natural world and the ways that learners come to understand their world. Novice learners also construct ideas about the natural world based, in part, on observations of objects, phenomena, and their interactions. With time, these ideas also become linked and tested through the learner's experiences and his or her interactions with the ideas of others. In the process, learners come to retain and develop some concepts and explanations, to reject others, and in turn to wonder about connections to new ideas and implications. Teachers have unique opportunities in science to help students wonder about the exciting natural world, experience and observe interesting objects and phenomena, explore meaningful theoretical ideas, and grow in scientific understanding. The school science laboratory is a unique resource that can enhance students' interest, knowledge of science concepts and procedures, and knowledge of important tools and skills that can develop new understanding. Experiences in the school laboratory can also help students glimpse ideas about the nature of science that are crucial for their understanding of scientific knowledge. These are among the reasons that *laboratory activities* (*practical activities* in British Commonwealth parlance) have had a prominent place in the science curriculum since early in the nineteenth century. A classical definition of school science laboratory activities that would have been acceptable in the nineteenth century and most of the twentieth is: *learning experiences in which students interact with materials or with secondary sources of data to observe and understand the natural world* (for example: aerial photographs to examine lunar and earth geographic features; spectra to examine the nature of stars and atmospheres; sonar images to examine living systems). The development and increasingly widespread use of digital computing technologies in school science near the turn of the twenty-first century provide new tools for gathering, visualizing, and reporting data and findings as well as important and new tools that can support learning. New tools also offer simulation resources for teaching and learning science. Some of these new tools and resources blur the interface between learning in the laboratory and learning with simulations that are representations of nature. In fact, work with simulations has caused some to perceive that school laboratory activities are themselves simulations of some of the things that scientists do (Lunetta, 1998). The new electronic tools and resources for teaching and learning associated with the school science laboratory also offer important new opportunities to study learning in science, and they warrant careful scholarly study by researchers in science education as we enter the twenty-first century.

## A HISTORICAL OVERVIEW

For almost 200 years, science educators have reported that laboratory activities can assist students in making sense of the natural world (Edgeworth & Edgeworth, 1811; Rosen, 1954). Over the years, many have argued that science cannot be meaningful to students without worthwhile practical experiences in the school laboratory. Unfortunately, the terms *school laboratory* or *lab* and *practical* have been used, too often without precise definition, to embrace a wide array of activities. Typically, the terms have meant experiences in school settings where students interact with materials to observe and understand the natural world. Some laboratory activities have been designed and conducted to engage students individually, and others have sought to engage students in small groups and in large-group demonstration settings. Teacher guidance and instructions have ranged from highly structured and teacher-centered to open inquiry. The terms have sometimes been used to include investigations or projects that are pursued for several weeks, sometimes outside the school, and on other occasions they have referred to experiences lasting 20 minutes or less. Sometimes laboratory activities have incorporated a high level of instrumentation, and at other times the use of any instrumentation has been meticulously avoided.

Historically, school *labs* have ranged from activities where data are gathered to illustrate a previously stated relationship to activities where students seek patterns or relationships in data they gather. In the early part of the twentieth century John Dewey and others in the progressive education movement energetically advocated an investigative and more utilitarian approach in learning. Through the 1950s, however, laboratory activities were used almost exclusively for illustrating information presented by the teacher and the textbook, and scholarly research on the educational effectiveness of the school laboratory was relatively limited.

Subsequently, in the science education reform era of the 1960s in both the United States and the United Kingdom, major science curriculum projects developed "new" curricula intended to engage students in investigation and inquiry as a central part of their science education. In that period, major curriculum projects used the learning theories of Jerome Bruner, Robert Gagne, and Jean Piaget to justify curricula emphasizing student inquiry and hands-on activities. Projects, including those of the Physical Science Study Committee and the Biological Sciences Curriculum Study in the United States and Nuffield in the United Kingdom, developed inductive laboratory activities as a fundamental part of the science curriculum. In these projects the laboratory was intended to be a place for inquiring, for developing and testing theories and assertions, and for practicing "the way of the scientist." George Pimentel (see Merrill & Ridgeway, 1969) noted that in the CHEMStudy project, the laboratory was designed to help students gain a better idea of the nature of science and scientific investigation.

For more than a century, laboratory experiences have been purported to promote central science education goals, including the enhancement of students' understanding of concepts in science and its applications; scientific practical skills and problem-solving abilities; scientific "habits of mind"; understanding of how science and scientists work; and interest and motivation. Periodically, and particularly in the late 1970s and the early 1980s, serious questions were raised about the effectiveness of the school laboratory in promoting science learning (Bates, 1978; Hofstein & Lunetta, 1982). Questions emanated from multiple sources both within the science education community and beyond. Research on learning brought forth knowledge of learners' development and new insights about the learning of science concepts. Scholarly efforts identified serious mismatches between stated goals for science education and the learning outcomes visible in school graduates. Particularly noteworthy for laboratory learning, researchers reported that students regularly performed school science experiments with purposes in mind that were very different from those articulated by science educators for such experiences. In addition, comprehensive analyses of laboratory handbooks also provided evidence that major mismatches existed between goals espoused for science teaching and the behaviors implicit in science laboratory activities associated with major curriculum projects (Tamir & Lunetta, 1981). Lunetta and Tamir (1979) were among those who recommended greater consistency between goals, theories, and practices in the learning and teaching of science. In addition, important perspectives about the nature of science began to be applied to science education more broadly and to science laboratory activities in particular. These too fueled many concerns about the ways introductory sciences should be taught to promote learning with scientific understanding.

Nevertheless, in spite of a long series of reform efforts incorporating important elements from the history of science, the predominant pattern of science teaching visible in schools through the turn of the twenty-first century has omitted the story of science. Instead, the science visible in schools has focused on "covering" knowledge of science topics and limited problem-solving skills. Within that framework laboratory activities have engaged students principally in following ritualistic procedures to verify conclusions previously presented by textbooks and teachers. In general, students have had limited freedom and time to explore and to make sense of phenomena. Objectives articulated for teaching and for student behaviors have often focused on specific tasks to be accomplished, such as "doing the density lab," rather than on the student learning that is to be accomplished, such as "learning about the relationships between mass and volume for different materials." Duschl and Gitomer (1997, p. 65) noted that teachers tend to see teaching as "dominated by tasks and activities rather than conceptual structures and scientific reasoning." Kesidou and Roseman (2002) reported that contemporary curricula did not engage students in laboratory activities consistent with goals for learning. Weiss et al. (2003, p. 1) reported that 59% of the science and mathematics lessons they observed were low in quality, often reflecting "passive learning" and "activity for activity's sake." This emphasis on dozens of tasks and activities rather than on conceptual understanding results in what Schmidt et al. (1999), analyzing the results of the Third International Mathematics and Science Study (TIMSS), called an unfocused science curriculum in the United States that is "a mile wide and an inch deep."

To complicate matters, science education studies have not always helped to distinguish between and link important ends (learning outcomes that are sought) and means to those ends (teaching resources and strategies such as specific kinds of investigative activities in the laboratory). For example, significant changes in technologies since the 1980s have offered new resources for teaching and learning, but insufficient attention has been directed to critical examination of how these new technologies can enhance or confound experiences in the school laboratory. Further complicating research into school laboratory practices have been ambiguous use of terms such as *inquiry science teaching*, which may refer to teaching science *as* inquiry (helping students understand how scientific knowledge is developed) or teaching science *through* inquiry (having students take part in inquiry investigations to help them acquire more meaningful conceptual science knowledge). Inquiry investigations conducted by novices in school science laboratories differ in important ways from authentic scientific investigations conducted by expert scientists, and to enable development of the science education field, it is important for teachers and researchers in science education to define and use central technical terms precisely and consistently. Engaging students in laboratory *inquiry*, for example, has involved activities ranging from *highly structured* laboratory experiences to *open-ended* investigations in which students explore a question they may have articulated themselves. The nature of the guidance the teacher and the curriculum materials provide for the students is very important to the learning that occurs. Unfortunately, the guidance provided for students has often not been examined or described carefully in studies of laboratory learning; careful reporting of the nature of that guidance is one important factor in good research and development of laboratory work in science education.

## REVIEWS OF RESEARCH ON THE SCHOOL LABORATORY

The uniqueness of the laboratory as a medium for learning and teaching science has caused it to be the subject of many research studies and several reviews since the 1960s. The reviews referenced in this chapter include those published by Ramsey and Howe (1969), Bates (1978), Blosser (1980), Hofstein and Lunetta (1982), Tobin (1990), Hodson (1993), Lazarowitz and Tamir (1994), and Hofstein and Lunetta (2004). These reviews are sources of many literature citations that have not been included in this chapter because of space limitations.

Prior to the reform movements of the 1960s a latent assumption of many science educators and teachers was that students learn science by verifying or applying ideas in the school laboratory that were taught earlier in class. As noted in the preceding historical overview, curriculum projects developed during the reform movement in the 1960s were intended to promote greater focus on inquiry, interest, and conceptual understanding. A tacit assumption of scientists who led the curriculum reform movement of the 1960s was that students come to understand science ideas simply by performing activities, collecting data in the school laboratory, and then generalizing from the information collected; teachers and the "teacher-proof textbook" provided guidance in the process. Important changes did occur in the development of science curricula, teaching resources, and for a time in science teacher development workshops. However, in general, science teaching has continued to be relatively didactic and focused on delivering information.

Although the 1960s reforms were based, in part, on theories of learning, relatively little research in science education in that decade looked carefully at students' understanding of science concepts, attitudes, and possible causal factors associated with students' experiences in the science classroom and laboratory. Following an extensive review of the literature on the school laboratory, Ramsey and Howe (1969) wrote that science educators had come to expect that laboratory experiences "should be an integral part of any science course." They also noted that the nature of the best kinds of experiences and how these could be integrated with more conventional class work had not been objectively assessed. They claimed that as a result, implications for teaching based on research on laboratory-classroom learning were not available (p. 75).

Between the late 1960s and the 1980s hundreds of research papers and doctoral dissertations investigated variables in settings associated with teaching in the school science laboratory. Bates (1978) reviewed 82 studies on the role of the laboratory in secondary school science programs and wrote that the question of what laboratories accomplish that could not be achieved by less expensive and less-time consuming alternatives needed more research. He wrote (p. 74):

> Lectures, demonstrations, and laboratory teaching methods appear equally effective in transmitting science content;
>
> Laboratory experiences are superior for providing students skills in working with equipment;

> The laboratory appears to represent significantly different areas of science learning than content acquisition;
>
> Some kinds of inquiry-oriented laboratory experiences appear better than lecture/demonstrations or verification-type laboratories for teaching the process of inquiry. However teachers need to be skilled in inquiry teaching methods;
>
> Laboratories appear to have potential for nurturing positive students' attitudes.

Many of the studies on school laboratory learning conducted between 1960 and 1980 tended to assess students' knowledge of conventional science facts. In general, the studies did not take a careful look at the nature of students' learning or their perceptions of the purposes of their laboratory work, and they did not carefully assess students' understanding of the nature of science.

Hofstein and Lunetta (1982) wrote that "Past research studies generally examined a relatively narrow band of laboratory skills and the conclusions that were drawn may apply to a narrow range of teaching techniques, teacher and student characteristics, and learning outcomes" (p. 204). They argued that many research studies conducted since the 1960s suffered from a number of weaknesses, including selection and control of variables, group size, instrumentation selected for the research studies, and control over teacher's behavior and over the students' activities provided by the laboratory. In addition, they wrote that research failed to show simple relationships between experiences in the laboratory and students' learning. Most research studies conducted on the science laboratory failed to show advantages of the laboratory over other science teaching practices, but if differences did exist they were probably masked by confounding variables, by the use of insensitive research instrumentation, and/or by poor research design. For example, only seldom was attention given to the characteristics of the student sample (e.g., cognitive development) or the crucial nature of the teacher's laboratory teaching, expectations, and assessment practices. Hofstein and Lunetta (1982) outlined the need for new research that would provide more information about the important but complex relationships between goals for learning, teacher expectations and behaviors, and student learning outcomes.

The reviews by Bates (1978) and Hofstein and Lunetta (1982) cited several studies indicating that students enjoy laboratory work in some courses and that laboratory experiences have resulted in positive and improved student attitudes and interest in science. Among the studies reviewed, Hofstein et al. (1976) reported that students in Israel rated their personal involvement in the chemistry laboratory as the most effective instructional method for promoting their interest in chemistry when contrasted with teacher demonstrations, presentations, and classroom discussions. Other studies conducted in the 1970s and 1980s made similar claims. Ben-Zvi et al. (1977), for example, reported that chemistry students' personal involvement in chemistry laboratory investigations had been the most effective medium in their chemistry classes for promoting their interest in chemistry when contrasted with teacher's demonstrations, filmed experiments, classroom discussions, and teachers' lectures. In a study that examined why students enrolled in optional advanced high school chemistry courses, one of the key reasons offered was their experience with practical activities in the chemistry laboratory (Milner et al., 1987). These results are similar to findings reported in the United States (Charen, 1966; Johnson et al., 1974; Raghubir, 1979). In Nigeria, Okebukola (1986), using the Attitude toward Chemistry Laboratory Questionnaire (Hofstein et al., 1976), reported that greater participation in chemistry laboratory activities resulted in improved student attitudes toward chemistry learning in general and toward learning in the chemistry laboratory in particular.

By early in the 1990s, the pendulum of research within the science education literature had moved away from the affective domain and toward the cognitive domain, with special attention to conceptual change. Reflecting this shift, two comprehensive reviews that were published in the early 1990s (Hodson, 1993, and Lazarowitz & Tamir, 1994) did not discuss research focused on affective variables such as attitudes and interest. Nevertheless, some science educators continued to report studies indicating that laboratory work is an important medium for enhancing attitudes, stimulating interest and enjoyment, and motivating students to learn science (e.g., Freedman, 1997; Thompson & Soyibo, 2002). In 2004, the Attitude toward Chemistry Laboratory Questionnaire was administered in a study in which two groups of students were compared (Kipnis & Hofstein, 2005). The first student group performed inquiry-type chemistry investigations, and the second group performed more conventional, confirmation-type activities. Students in the inquiry group developed more positive attitudes toward learning chemistry than did the students who experienced the conventional treatment.

Since the early 1970s, researchers have studied students' perceptions of the *classroom learning environment* and its relationship to outcomes such as student achievement and attitudes (Fraser & Walberg, 1989). A valid and reliable measure for assessing students' perceptions of the *laboratory learning environment*, the Science Laboratory Environment Inventory was developed and validated by a group in Australia and used subsequently in studies conducted in several world locations. Fraser et al. (1993) reported that Australian students' perceptions of the laboratory learning environment accounted for significant differences in the variance in students' learning of science content beyond that attributed to differences in their abilities. Fisher, Henderson, and Fraser (1997) reported significant correlations between students' perceptions of the science laboratory learning environment and their attitudes and science achievement. Similar results were reported in an Australian study by Fraser et al. (1993). A study of this kind was also conducted on high school chemistry in Israel (Hofstein et al., 2001). The study revealed that students involved in a series of inquiry-type laboratory investigations in chemistry found the laboratory learning environment to be more open-ended and more integrated with the conceptual framework they were developing than did the students enrolled in conventional laboratory courses (control). In the inquiry group the gap between the actual learning environment and the students' preferred environment was significantly smaller than in the control group. These findings suggested that some kinds of practical experiences can promote a positive, healthy learning environment.

Tobin (1990) wrote: "Laboratory activities appeal as a way of allowing students to learn with understanding and, at the same time, engage in the process of constructing knowledge by doing science" (p. 405). To attain this goal he suggested that students should be provided opportunities in the laboratory to reflect on findings, clarify understandings and misunderstandings with peers, and consult a range of resources that include teachers, books, and other learning materials. His review reported that such opportunities rarely exist because teachers are so often preoccupied with technical and managerial activities in the laboratory. Similarly, Hodson

(1993) suggested that although teachers generally professed a belief in the value of student-driven, open, practical investigation, in general their teaching practices in the laboratory failed to support that claim. He also argued that the research literature failed to provide evidence that standard school laboratory activities encouraged knowledge construction. He was critical of the research literature: "Despite the very obvious differences among, for example, practical exercises designed to develop manipulative skills or to measure 'physical constraints', demonstration-type experiments to illustrate certain key-concepts, and inquiries that enable children to conduct their own investigations, there is a tendency for researchers to lump them all together under the same umbrella title of practical work" (p. 97). Tobin wrote that teachers' interpretations of practical activity should be elaborated, made a part of the research design, and reported, because a laboratory session could be open-ended inquiry in one classroom and more didactic and confirmatory in another teacher's classroom. Tobin (1990) and Hodson (1993) were among those who wrote that, in general, science teachers failed to create an environment that encouraged students to make sense of their laboratory experiences, to reflect on their own thinking and to explore new connections that eventually led to the desired conceptual understanding.

Based on their review of the laboratory literature, Lazarowitz and Tamir (1994) joined the long list of authors who indicated that the potential of the laboratory as a medium for teaching science is enormous. They wrote that the laboratory is the only place in school where certain kinds of skills and understanding can be developed. Yet, they are among those who have written that much of what actually occurs in contemporary school laboratory work is not consistent with important purposes of those laboratory activities (Kesidou and Roseman, 2002; Hart et al., 2000). Hodson (2001) wrote that although unique outcomes for laboratory/practical work were articulated in the recent past, the nature of students' experiences in the laboratory and related assessment practices remained relatively unchanged.

Tibergien et al. (2001) and Sere (2002) reported work in a long-term project (Lab-Work in Science Education) conducted in several European nations. They described similarities and differences in science education laboratory tasks in upper secondary schools in Europe. Sere (2002) wrote: "The intention of the [study] was to address the problem of the effectiveness of lab-work, which in most countries is recognized as being essential to experimental sciences, but which turns out to be expensive and less effective than wished" (p. 624). Information on practice was gathered through 23 case studies, surveys, and a tool that helps to map and describe the laboratory work domain. Sere reported that the objectives typically articulated for laboratory work (i.e., understanding theories, concepts, and laws; conducting various experiments; learning processes and approaches; and applying knowledge to new situations) were too numerous and comprehensive for teachers to address successfully in individual laboratory sessions. In response, she suggested that the scope of the objectives for specific laboratory activities should be limited. Science curriculum developers and science teachers should make conscious choices among specific learning objectives for specific laboratory activities and clearly articulate the specific objectives for their students. Sere's "targeted lab-work" project produced a series of recommendations, including the need for each laboratory activity to be supported by a particular strategy organized within a coherent long-term program plan with varied kinds of laboratory work. Subsequently, the Hofstein and

Lunetta (2004) review examined themes emerging at the beginning of the twenty-first century. These themes are explored in the section that follows.

## RESEARCH ON THE LABORATORY: AN ANALYSIS OF EMERGING THEMES

Early in the twenty-first century we are in a new era of reform in science education. Once again, the content and pedagogy of science learning and teaching are being scrutinized, and new standards intended to shape meaningful science education have emerged. The National Science Education Standards (National Research Council, 1996) and other science education literature (Lunetta, 1998; Bybee, 2000; Hodson, 2001; Hofstein & Lunetta, 2004) emphasized the importance of rethinking the role and practice of school laboratory work in science teaching. To do so is timely because in recent decades we have learned much about human cognition and science learning (Bransford et al., 2000). In addition, learning through inquiry (National Research Council, 2000) has important potential for teaching science, but it also poses challenges for teachers and learners (Krajcik et al., 2001).

Recent scholarship especially relevant to the school science laboratory has focused on the following themes elaborated in this section:

- Articulating and implementing more explicit goals for student learning;
- Applying learning theory organizers
- Developing classroom communities of inquirers
- Developing students' understanding of the nature of science
- Developing inquiry and learning empowering technologies
- Articulating and implementing more explicit goals for student learning

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In recent decades, educators have articulated with increasing regularity and clarity that decisions in teaching, assessment, and selection of curriculum resources should be driven by the learning outcomes sought for students. Goals for student learning continue to be explicated, most recently labeled as science standards. As noted earlier in the historical overview of this chapter, expectations articulated for school science laboratory learning since the nineteenth century have included the goals reflected in the first four bulleted items in Table 15.1. Over time, however, understanding of these goals and of how to implement them has developed substantially.

In 1983, the National Commission on Excellence in Education (1983) published *A Nation at Risk: The Imperative for Educational Reform*. This report offered recommendations for schooling in the United States that promoted the movement toward national science standards. Although the goal of promoting understanding of the nature of science has also been articulated for the better part of 100 years, in the last 20 years of the twentieth century, that goal became increasingly prominent. The *Standards* and increasing numbers of publications advocated that school science should enable graduates to understand methods of scientific inquiry, reasoning, and the nature of science (see, e.g., Duschl, 1990; Klopfer, 1969; Matthews, 1994).

Acknowledging the importance of goals for learning, science education researchers increasingly focus on factors associated with learning outcomes, and they

**TABLE 15.1**
**Principal Goals for Learning in the School Laboratory**

Promote the development of students' scientific knowledge, problem-solving abilities, and habits of mind, including:

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- Conceptual knowledge
- Practical skills and problem-solving abilities
  - Now expanded to include:
  - Argumentation from data (*procedural knowledge*)
  - Knowledge of how science and scientists work
- Interest and motivation
- Understanding methods of scientific inquiry and reasoning
  - Now expanded to include the nature of science.

try to examine the nature of teaching strategies and behaviors that promote the learning outcomes that are sought. Some have employed new social science research methodologies that can shed light on the complex factors associated with learning and teaching science in school settings. Many researchers have also sought theoretical organizers to make sense of particular strategies and to inform curriculum development, teaching, and research. These efforts have occurred while substantive changes have been under way in society, in school and technology environments, and in what we know about teaching and learning science. The importance of keeping learning outcomes in mind is illustrated in John Goodlad's (1983) extensive study of schooling. His critical analysis of observations made in over 1,000 classrooms illustrated the chasm between statements of goals for learning and what so often happens in school laboratory experiences:

> One would expect the teaching of . . . science in schools to provide ample opportunities for the development of reasoning: deriving concepts from related events, testing in a new situation hypotheses derived from examining other circumstances, drawing conclusions from an array of data, and so on. Teachers listed those skills and more as intended learnings. We observed little of the activities that their lists implied, and teachers' tests reflected quite different priorities—mainly the recall of information. The topics that come to mind as representing the natural . . . sciences appear to be of great human interest. But on the way to the classroom they are apparently transformed and homogenized into something of limited appeal. (p. 468)

Similarly, research that focused on learning in the laboratory in the late twentieth century reported that mismatches regularly occurred between teachers' perceived goals for practical work and students' perceptions of such activities (Wilkenson and Ward, 1997; Hodson, 1993, 2001). Based on evidence that the goals of instruction are more likely to be achieved when students perceive those goals, Wilkenson and Ward concluded that teachers should be much more attentive to helping students understand the general and specific goals of each laboratory activity. Furthermore, because specific learning objectives are often different from one investigation to another, students should be helped to understand the purposes for each investigation in a *pre-lab* session, and they should review those purposes in *post-lab* reporting and discussion of their findings. However, Hodson (2001) observed that teachers often do not do in laboratories what they say they intend to do. Thus, as Eisner (1985, p. 59) wrote, “In the final analysis, what teachers do in the classroom and what students experience define the educational process.”

Earlier, based on analyses of student laboratory guides, Tamir and Lunetta (1981) wrote that, in spite of attempts to reform curricula, students worked too often as technicians following “cookbook” recipes in which they used lower level skills; they were seldom encouraged to discuss hypotheses, propose tests, and engage in designing and performing experimental procedures. Rarely, if ever, were students asked to formulate questions to be investigated or even to discuss sources of error and appropriate sample size. Students’ performance in practical activities generally was not assessed, nor were students asked to describe or explain their hypotheses, methodologies, or the nature and results of their investigations (Hofstein & Lunetta, 1982). Science education research in the 1980s showed that students tended to perceive that following the instructions, getting the right answer, or manipulating equipment and measuring were the principal purpose for a school science laboratory. However, they failed to perceive the conceptual and procedural understandings that were the teachers’ intended goals for the laboratory activities. The students often failed to understand the relationship between the purpose of the investigation and the design of the experiment. Students rarely wrestled with the nature of science and how it underlies laboratory work, including the interpretation of data; they did not connect their laboratory activity with what they had done earlier, and they seldom noted 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; Tasker, 1981). To many students, a laboratory activity has meant manipulating equipment but not manipulating ideas. More recent content analyses of published laboratory guides continue to suggest that students focus on relatively low-level tasks in the laboratory. For example, Domin (1998) analyzed contemporary printed chemistry laboratory guides and reported that they did not appear to actively engage students’ higher level cognitive activities—such as addressing issues related to the assumptions and design underlying the investigation or the scientific justification supporting findings. To remediate discrepancies between goals for learning and the structure of labs and relevant teaching practices, research studies must be conducted to understand the sources of these discrepancies and to develop more effective practices.

To these ends, promising scholarship has ensued. Some of these efforts, linked with learning theory, have focused on helping students articulate their ideas and explanations, reason from data, and improve the quality of their argumentation in school science (Osborne et al., 2004; Kanari & Millar, 2004; Reiser et al., 2001). The research has included the development and study of new software tools designed to support student inquiry and science learning associated with the school laboratory. These activities provide insights for teachers and researchers on the nature and development of students’ understanding as well as new resources for teaching and learning science. This work is elaborated later in this chapter (*Developing inquiry and learning empowering technologies*).

## APPLYING LEARNING THEORY ORGANIZERS

Since the curriculum reform era in the 1960s, science educators have recognized with increasing clarity the importance of identifying theories of learning that can provide guidance for research, curriculum development, and teaching. Developmental learning theory had a powerful influence on the role of the laboratory and on science education scholarship beginning in the 1960s. While more contemporary theories have been developed, developmental theory can continue to inform teachers' decisions regarding the selection and placement of laboratory experiences to promote the growth of students' reasoning abilities. For example, the three-phase Learning Cycle teaching model (Karplus, 1977; Schneider & Renner, 1980), grounded primarily in developmental learning theory, can guide teachers in providing initial exploration experiences with materials and phenomena for their students that can serve as a foundation for introducing science concepts. In the final application phase of the model, students are encouraged to explicitly link their understandings to questions and new situations. The learning cycle model was studied extensively and shown to promote many science education goals for learning (Abraham, 1982; Ward & Herron, 1980; Purser & Renner, 1983).

In the closing decades of the twentieth century a series of teaching models grounded in learning theories incorporated increasing knowledge of how people learn. These models were designed to guide teachers in selecting, planning, and sequencing their teaching, work in the school laboratory, and interactions with students to promote desired learning outcomes. Nussbaum and Novick (1982), for example, asserted that their model was an improvement on the learning cycle because it emphasized explicit identification of students' conceptual frameworks and their assumptions underlying those frameworks. A goal of their model was to help students become aware of their conceptual frameworks and assumptions and of how their frameworks differed from those of others. Like Erickson (1979), they emphasized the importance of creating conceptual conflict through laboratory experiences with observations contrary to what students tend to expect.

The Generative Learning model (Osborne and Freyberg, 1985) emphasized the need for teachers to consider their own personal explanations of the ideas the students were to study and contrast their ideas with the views of scientists on that topic. They also suggested ways teachers could ascertain the students' thinking on the topic early in the teaching sequence in order to help the students identify differences in their observations and interpretations in laboratory investigation and those of others. The *5-E model* (Bybee, 1997) advocated two phases beyond those of the learning cycle, *engagement* and *evaluation*. The engagement phase is similar to the first phase in the Nussbaum and Novick and the Osborne and Freyberg models in that it emphasizes the importance of engaging students' prior knowledge and experiences. The fifth and final *evaluation* phase reflects constructivist perspectives regarding the tenacity of learners' prior ideas; it involves assessing students' understanding via performance on a relevant task.

Research on the effects of teaching models on learning can have important implications for how teachers should implement laboratory activities. For instance, promoting students' understanding of scientific concepts demands that teachers have a rich scientific understanding of those concepts in addition to the pedagogical understanding and skills needed to use the teaching model (Tobin & Garnett, 1988). Hence, teachers' understanding of relevant science concepts is another important variable that should be, but rarely has been, examined and discussed in research studies on the laboratory. Additional empirical research is needed to examine learning outcomes more carefully and the specific elements of teaching that are most effective in promoting desired learning before, during, and following laboratory experiences.

When well planned and effectively implemented, science education laboratory and simulation experiences situate students' learning in varying levels of inquiry requiring students to be both mentally and physically engaged in ways that are not possible in other science education experiences. Teaching science as inquiry and through inquiry is at the heart of science education reform documents. Such inquiry reflects what we now know about how people learn science. Understanding how students learn and why they often struggle in learning what teachers intend is the foundation for effective teaching (Bransford et al., 2000). For instance, Driver (1997) noted:

> Our optimism about what children ought to be able to do stems perhaps from rather deep seated views about learning. And that as long as the expert tells the story clearly and that the person who is learning is listening and paying attention then they will automatically build up the understanding that the expert has. Now all our current knowledge in cognitive science, and in cognitive psychology, and in science education is telling us that simply does not happen. Children may well be listening, paying attention to what is being said or what they are reading in a book, but they are construing it in different ways to the ways that the teacher intended. And that is the issue we have to deal with. [AQ1]

Constructivist learning theory suggests that learners use ideas and constructs already in their minds to make sense of their experiences. Learning is an active, interpretive, iterative process (Bransford, et al., 2000). Gunstone (1991), however, wrote that helping students develop scientific ideas from practical experiences is a very complex process and that students generally did not have sufficient time or encouragement to express their interpretations and beliefs and to reflect on central ideas in the laboratory. Research on learning in the school laboratory makes it clear that to understand their laboratory experiences, students must manipulate ideas as well as materials in the school laboratory (White & Gunstone, 1992), and they must be helped to contrast their findings and ideas with the concepts of the contemporary scientific community. Manipulating materials in the laboratory is not sufficient for learning contemporary scientific concepts, and this accounts for the failure of "cookbook" laboratory activities and relatively unguided discovery activities to promote desired scientific understanding. Expecting students to develop scientific understanding solely though their laboratory experiences reflects misconceptions of the nature of science (Wolpert, 1992; Matthews, 1994) and how people learn science. Several studies suggested that although laboratory investigations offer excellent settings in which students can make sense of phenomena and in which teachers can better understand their students' thinking, laboratory inquiry alone is not sufficient to enable students to construct the complex conceptual understandings of the contemporary scientific community (Lunetta, 1998). In the laboratory, students should be encouraged to articulate and share their ideas to help them perceive discrepancies among their ideas, those of their classmates, and those of the scientific community. Driver (1995) wrote: "If students' understandings are to be changed toward those of accepted science, then intervention and negotiation with an authority, usually a teacher, is essential." [AQ2]

At the end of the twentieth century there was increasing understanding from cognitive sciences that learning is contextualized and that learners construct knowledge by solving genuine, meaningful problems (Brown et al., 1989; Roth, 1995;

Williams & Hmelo, 1998; Wenger, 1998; Polman, 1999). The school science laboratory can offer students opportunities to have some control of their activities, enhancing their perception of *ownership* and *motivation* (Johnstone and Al-Shuaili, 2001). It can be an environment particularly well suited for providing a meaningful context for learning, determining and challenging students' deeply held ideas about natural phenomena, and constructing and reconstructing their ideas. Though a complex process, meaningful learning in the laboratory *can* occur if students are given sufficient time and opportunities to interact, reflect, explain, and modify their ideas (Barron et al., 1998). Engaging in *metacognitive* behaviors of this kind enables students to elaborate and to apply their ideas; the process can promote conceptual understanding as well as the development of problem-solving skills. The challenge is to help learners take control of their own learning in the search for understanding while providing opportunities that encourage them to ask questions, suggest hypotheses, and design investigations, "minds-on as well as hands-on" (Gunstone, 1991). That theme has been pursued and reported in several research studies, including *Designing Project-Based Science* (Polman, 1999).

In moving students toward more "minds-on" engagement in the laboratory (including problem solving, reflecting on the meaning of data, and decision making, etc.), we now understand that teachers must sequence complex ideas and experiences (scaffolding) in ways that enable students to engage meaningfully in these activities. In doing so, teachers need to pay close attention to students' behaviors and what they are saying. They can then respond with pedagogical decisions that will help students make connections, enabling them to achieve desired learning outcomes. An important area of contemporary scholarship involves the research and development of software tools that support the scaffolding of ideas and promote dialogue. These tools are discussed in the section on Learning Technologies later in this chapter.

Emerging attention to a social constructivist theoretical framework has special potential for guiding teaching in the laboratory (e.g., Tobin, 1990; Lunetta, 1998). Social learning theory emphasizes that learning is situated in interactions with those around us, and conceptual development is associated with the medium of language. Thus, learning depends, in part, on interactions with adults and peers. Social learning theory makes clear the importance of promoting group work in the laboratory so that meaningful, conceptually focused dialogue takes place between students as well as between the teacher and students. Moreover, laboratory experiences in which students discuss ideas and make decisions can present many opportunities for teachers to observe students' thinking as they negotiate meaning with their peers. Carefully observing students' actions and listening to their dialogue creates opportunities for teachers to focus questions and make comments within learners' zones of proximal development (Vygotsky, 1978, 1986; Duschl & Osborne, 2002) that can help the students construct understandings that are more compatible with the concepts of expert scientific communities.

## DEVELOPING CLASSROOM COMMUNITIES OF INQUIRERS

The school laboratory is particularly well suited to cooperative investigation of scientific phenomena and relationships when teachers engage their students intellectually as a community of learners. The inquiring community includes the teacher and occasionally expert consultants (Penner et al., 1998; Roth & Roychoudhury, 1993). The importance of promoting *cooperative learning* in the science classroom and laboratory received much attention during the 1980s (e.g., Johnson and Johnson, 1985; Lazarowitz & Karsenty, 1990). Large numbers of studies demonstrated distinct benefits in students' achievement and productivity when cooperative learning strategies were successfully utilized in the classroom-laboratory. 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 reported that the more informal atmosphere and opportunities for interaction among students and their teacher and peers can promote a healthy learning environment conducive to meaningful inquiry and collaborative learning (Tobin, 1990; DeCarlo & Rubba, 1994). In a study that compared high school chemistry students' ability to formulate questions associated with a science reading and with a science investigation, Hofstein et al. (2005) reported that students who had experience asking questions in a laboratory inquiry-focused course outperformed those in control groups in their ability to ask more and better questions.

The Lunetta (1998) and Hofstein and Lunetta (2004) reviews noted research indicating that the school laboratory offers important opportunities for interaction between students and their teacher and among peers that can be conducive to meaningful inquiry and collaborative learning that results in desired cognitive growth. Research on the school laboratory conducted early in the twenty-first century examined ways to promote and support collaboration among students while they engage in laboratory inquiry or inquiry with the laboratory data gathered by scientists (see, for example, Land & Zembal-Saul, 2003; Edelson et al., 1999). This research has resulted in the development of new software tools that promise to enhance students' inquiry and reflection on the process. Land and Zembal-Saul, for example, reported that use of Progress Portfolio software prompted learners to articulate and connect their experimental findings back to the larger driving questions. "The negotiation and struggle that ensued regarding the significance of the data promoted explanation, justification and reflective social discourse." Research and findings associated with the development of the software tools are discussed in the technology section later in this chapter. [AQ3]

Through the collaboration, reflection, and discussion associated with investigation, students can develop scientific knowledge, and they can begin to glimpse the collaborative nature of an expert scientific community. These are learning outcomes that are now thought to be very important in introductory science. Promoting and examining reflective social discourse in the laboratory is a particularly important area for further science education research, especially since observations of science laboratory classrooms today continue to suggest that insufficient attention is given to promoting collaboration, reflective discourse, and community negotiation.

## DEVELOPING STUDENTS' UNDERSTANDING OF THE NATURE OF SCIENCE

While promoting students' understanding of the nature of science had been articulated as a science learning goal for decades, that goal acquired greater significance (see, for example, Duschl, 1990) in the last 30 years of the twentieth century (see also Chapter 29 in this Handbook). Several reasons relevant to learning in the school laboratory have been discussed in the literature for promoting understanding of the nature of science (Abd-El-Khalick & Lederman, 2000; McComas et al., 1998; Matthews, 1994). Some have argued that appropriate laboratory experiences have an important role to play in developing students' understanding of the nature of science, whereas other evidence suggests that the relatively widespread lack of understanding of scientific philosophical and procedural ideas by both teachers and students has interfered with learning during laboratory inquiry. The outcomes of laboratory investigations in which students have been expected to "discover" accepted scientific relationships have often disappointed students, teachers, and researchers, in part because of mistaken notions regarding the nature of science and how people learn science concepts. Believing that students who carefully perform particular laboratory investigations will come to the same understanding as scientists reflects a naive empiricist view of scientific knowledge (Lederman et al., 1998; Wellington, 1981). Rowe and Holland (1990) described a student's frustration in trying to reconcile science ideas with what is observed in the real world:

> What is this game that scientists play? They tell me that if I give something a push it will just keep on going forever or until something pushes it back to me. Anybody can see that isn't true. If you don't keep pushing, things stop. Then they say it would be true if the world were without friction, but it isn't, and if there weren't any friction how could I push it in the first place? It seems like they just change the rules all the time. (p. 87)

This commentary illustrates how understanding aspects of the nature of science is crucial to helping students make sense of their school laboratory experiences. The tendency in scientific writing and science textbooks to idealize conditions in the natural world is counter-intuitive to everyday thinking (Cromer, 1993; Wolpert, 1992; Matthews, 1994; Toulmin, 1972).

Crucial for tapping the potential of laboratory experiences is understanding that the underlying assumptions and theoretical frameworks that shape the understanding and concepts of the expert scientific community are often very different from ideas commonly held throughout the culture; these large differences influence what students observe and the sense they make from their laboratory work. Informed science educators understand that humans tried to understand the natural world for thousands of years prior to the western Renaissance. The subsequent development of contemporary scientific worldviews spanned hundreds of years and resulted in significant changes (paradigm shifts) in our understanding of science concepts and in our understanding of science. The long and counter-intuitive history of science helps to explain some of the misconceptions held regularly by students and some teachers, and the considerable challenges to be addressed in helping novice learners to understand contemporary scientific concepts.

Making sense of school laboratory experiences often requires that learners and their teachers make conscious efforts to avoid conventional assumptions. Matthews (1994) and others have pointed out that scientific knowledge is based on several assumptions that conflict with commonly held ideas. The following widely held views, for example, can interfere with intended learning in school laboratory settings:

*Processes in the natural world bring about a suitable final state*. Students holding this view may search for explanations that are unnecessarily teleological, thus interfering with their understanding of contemporary scientific explanations.

*Natural processes are activated and controlled by spiritual influences*. This perspective is evident in the difficulty many students and some teachers have in interpreting evidence the scientific community presents in support of biological evolution.

*Knowledge is fixed and unchanging*. This assumption is evident in the difficulty many people have in understanding how well-accepted scientific knowledge based on sound research can be modified on the basis of new empirical evidence or the reinterpretation of evidence gathered in the past.

*Scientific knowledge comes simply from observing natural phenomena*. This assumption is evident in students' difficulties relating formal science concepts to the "real" world. For instance, the student's frustration with objects in motion referenced above (Rowe and Holland, 1990) illustrates how this assumption can interfere with desired science learning.

*Scientific knowledge claims are validated solely by their successful predictions*. Idealized science ideas do not always appear to result in accurate predictions, and some ideas that do provide accurate predictions (e.g., Ptolemaic astronomy) have been abandoned in favor of alternative ideas (e.g., Copernican astronomy). Accurate prediction is part of, but not the only factor in, developing contemporary scientific knowledge.

Many students and some teachers consciously or subconsciously maintain some or all of these assertions while learning and teaching science. If the assumptions are left unexamined, they are likely to interfere with the learning outcomes sought from school laboratory activities. Effective use of laboratory experiences, on the other hand, can help students and their teachers clarify the nature of science and how it differs from other ways of knowing. Informed and relevant discussions about the nature of science in the context of laboratory work can help students make sense of their laboratory experiences and better understand conceptual and procedural scientific knowledge. The interplay between conceptual and procedural knowledge is illustrated in Rudolph and Stewart's (1998) analysis that "understanding evolutionary biology, and science more generally, requires learners to become familiar with the metaphysical assumptions and the methodological processes that Darwin laid out. Theoretical context and scientific practice are two interdependent views of a single entity" (p. 1085).

Duschl (1987) and others have argued that effective inquiry teaching demands that science teachers have an understanding of the nature of science, that is, that an understanding of relevant philosophical presuppositions is often necessary to conduct laboratory work and to help students interpret results scientifically. Making the most of laboratory experiences requires that both teachers and students understand that many science ideas do not follow simply from observing natural phenomena. What this means for effective school laboratory experiences is that teachers must help their students come to understand the epistemological (how knowledge is constructed and justified) and ontological (nature of reality) assumptions underlying scientific knowledge and the rationale for holding those assumptions while doing science. That said, these issues are complex indeed and warrant further substantial and systematic study of their implications.

A number of recent studies relevant to the school laboratory have focused on enhancing the quality of students' argumentation from data. Kanari and Millar (2004), reporting on how students collect and interpret data, wrote that "an analysis of the sample students' performance on the practical tasks and their interview responses showed few differences in performance when investigating situations of covariance and non-covariation. . . . Investigation of non-covariation cases revealed . . . the students' ideas about data and measurement and their ways of reasoning from data. Such investigations provide particularly valuable contexts for teaching and research" (p. 748). Several of the contemporary studies that examine students' argumentation use new software tools designed to focus students' attention on the ways they justify their own assertions during science investigations. Based on data from a study utilizing such software, Sandoval and Morrison (2002) wrote: "Overall, students held a view of science as a search for right answers about the world. Yet the inconsistency of individuals' responses undermines the assumption that students have stable, coherent, epistemological frameworks. . . . Combined with previous work, our findings emphasize the crucial role of an explicit epistemic discourse in developing students' epistemological understanding." Informed use of this kind of technology tool in teaching has the potential to promote improved understanding of science concepts and perhaps of the nature of science for students. Such tools also offer a window for researchers into students' beliefs, understanding, and how students' understanding can become more scientific.

As noted earlier, research has shown that students are unlikely to develop desired understandings about the nature of science simply by taking part in inquiry experiences. Based on empirical research, Drive, et al. (2000) are among those who have suggested that making argumentation a more central and explicit part of learning may improve students' inquiry abilities while supporting their epistemological development. Duschl (2000) wrote that the nature of science can be made explicit when students examine, argue about, and discuss the nature of good evidence and decide between alternatives. Others have written that students learn about the nature of science through an explicit reflective approach (Abd-El-Khalick & Lederman, 2000; Schwartz & Lederman, 2002). Sandoval and Reiser (2004) suggested "engaging students in the reasoning and discursive practices of scientists, not necessarily the exact activities of professional scientists."

Examining these issues is an important frontier area in science education scholarship. Substantive, systematic research is warranted to clarify the complex issues involved. Such research should shed light on how to use school laboratory experiences to help students understand important aspects of the nature of science and on how to help them apply their understanding of the nature of science in laboratory investigations and in the world around them. Perspectives on the relevant nature of science issues are elaborated in this *Handbook* in Chapter 29, and the development and use of software tools especially relevant to learning in the school science laboratory are discussed in the section that follows.

## DEVELOPING INQUIRY AND LEARNING EMPOWERING TECHNOLOGIES

In the early 1980s digital technologies became increasingly visible in school laboratories and were recognized as important tools in school science (Lunetta, 1998; Kozma et al., 2000). Much evidence now documents that using appropriate technologies in the school laboratory *can* enhance learning, and important research on learning empowering technologies is the focus of this section. That said, an initial cautionary note is fitting, since evidence also documents that inappropriate use of even simple technology tools has interfered with meaningful science learning (Olson and Clough, 2001; Hofstein and Lunetta, 2004). When a device is introduced prematurely, before students have made sense of the underlying science concepts, there is evidence that the device or tool may serve as a black box that interferes with students' perceptions of what is happening and hinder their understanding of important scientific ideas. To cite one widely viewed example, after having used a bulb holder (bulb socket) in a simple *batteries and bulbs* activity intended to illustrate electric circuits, interviewers in a very well-known video (Annenberg/CPB, 1997) showed clearly that one of the articulate and talented students in an honors high school physics class thought the bulb holder was an essential but mysterious (almost magical) part of the electric circuit. The teacher in the video had made the bulb holders available to help the students construct a simple electric circuit in the laboratory. The student interviewed, however, did not understand the construction and function of the very simple bulb holder. Her failure to have that understanding interfered with her ability to interpret simple observations, to understand the circuit as a whole, and to predict outcomes when the circuit was connected. In this powerful example, if the student had had the opportunity to connect the light bulb in a simple circuit *before* she had access to bulb holders, or if the bulb and bulb holder had been dissected prior to their use in circuits, she then might have perceived the utility and function of bulb sockets that could assist her in connecting and observing bulbs in more complex electric circuits. This video presents very clear and powerful evidence that teachers must seek information about students' understanding of laboratory materials and devices as well as their understanding of the relevant science concepts and then merge that information with the goals sought for students' learning in the laboratory-classroom.

Computer tools, of course, are far more complex and perhaps more "mysterious" than is the functioning of the simple bulb holder that was a principal source of the misunderstanding displayed in the video. Computer tools can promote learning when their role and function are understood. They can be very helpful, for example, in displaying real-time graphic representations and functional relationships. Linked to such graphic displays, the computer can serve as a powerful interfacing tool in the laboratory. However, when a student does *not* understand the purpose and functioning of that interfacing tool (perhaps, for example, if the interfacing device had been an electric current meter in the electric circuit discussed in the preceding paragraph), the use of the powerful digital interfacing tool at that particular time could have *interfered* with the student's development of the understanding sought by the teacher more than the light socket did.

*Inquiry empowering technologies* (Hofstein & Lunetta, 2004) have been developed and adapted to assist students in gathering, organizing, visualizing, interpreting, and reporting data. Some teachers and students also use new technology tools to gather data from multiple trials and over long time intervals (Friedler et al., 1990; Lunetta, 1998; Krajcik, Blumenfeld, Marx, & Soloway, 2000; Dori et al., 2004). Increasingly, students and their teachers use software to visualize data and functional relationships. Students can examine graphs of relationships generated in real time as an investigation progresses and examine the same data in spreadsheets and in other visual representations. They can use similar software tools such as BGuILE (Reiser et al., 2001), designed for use in biology teaching and learning, to visualize and examine relationships in scientific data gathered by expert scientists in other locations. When teachers and students properly use inquiry empowering technologies to gather and analyze data, students have more time to observe, reflect, and construct the conceptual knowledge that underlies their laboratory experiences. The associated graphics also offer visualization resources that can enhance students' experiences with authentic activities while promoting deeper conceptual understanding (Edelson, 2001). When students have the time and when the activity is valued by the teacher and by high-stakes assessment, students can examine functional relationships and the effects of modifying variables; they can also make and test predictions and explanations. Technologies that offer instantaneous display of data as it is gathered can offer opportunities through which students may be helped to understand systemic functional relationships and more holistic relationships among variables. Using appropriate high-technology tools can enable students to conduct, interpret, and report more complete, accurate, and interesting investigations. Such tools can also provide media that support communication, student-student collaboration, the development of a community of inquirers in the laboratory-classroom and beyond, and the development of argumentation skills (Zembal-Saul et al., 2002).

Two studies are among several that illustrate the potential effectiveness of particular technology in school science. Nakleh and Krajcik (1994) investigated how students' use of chemical indicators, pH meters, and microcomputer-based laboratories (MBL) affected their understanding of acid-base reactions. Students who used computer tools in the laboratory emerged with better ability to draw relevant concept maps, to describe the acid-base construct, and to argue about the probable causes of why their graphs formed as they did. Dori et al. (2004), developed a high school chemistry unit in which the students pursued chemistry investigations with the use of integrated desktop computer probes. In a pre-post design study, these researchers found that students' experiences with the technology tools improved their ability to pose questions, to use graphing skills, and to pursue scientific inquiry more generally.

In addition to developing new applications of technologies that help students gather, visualize, and analyze data, other important software tools have also been designed and developed near the turn of the twenty-first century to empower learning. As noted earlier in this chapter (*Applying learning theory organizers* section), helping students develop understanding of scientific concepts is frequently a very complex task. We now understand that teachers must sequence complex ideas and experiences in ways that enable students to engage with those ideas through a series of activities and interactions. In contemporary cognitive parlance, teachers and curriculum resources must *scaffold* complex ideas and experiences in ways that enable students to engage, interact, and reflect meaningfully in these activities in order to construct meaningful scientific knowledge. A relatively new area of contemporary scholarship in science education attempts to integrate what we know about how people learn science with the use of new computer software tools that complement and intersect learning in the school laboratory. This research is associated with the design, development, and use of interactive software tools that promote dialogue, relevant activities, and the scaffolding of scientific ideas and students' construction of scientific knowledge (Tabak, 2002; Reiser et al., 2001; Edelson, 2001; Linn, 2000). Davis and Linn (2000) wrote that prompting students (via their Knowledge Integration Environment software) to reflect on their ideas significantly increased performance and knowledge integration. Sandoval and Reiser (2004) wrote that their findings suggest that epistemic tools can play a unique role in supporting students' inquiry and are a fruitful means for studying students' scientific epistemologies.

As noted earlier in this chapter, the use of Progress Portfolio software prompted learners to articulate and connect their experimental findings back to the larger driving questions (Land & Zembal-Saul, 2003). "The negotiation and struggle that ensued regarding the significance of the data promoted explanation, justification and reflective social discourse that can be observed" and studied by teachers and researchers. Related applications of software with important potential to empower student learning include engaging students in using software presentation tools to organize, discuss, and report their investigations, data, findings, and explanations of those findings to share with others. Research on the appropriate use and development of powerful new technology tools is needed to shape the use and development of state-of-the-art technologies, teaching strategies, and curricula that can facilitate important and meaningful science learning.

## TOWARD ASSESSMENT RESOURCES AND STRATEGIES

Over the years several researchers have suggested that the laboratory is not only a unique resource for teaching and learning, but also a unique vantage point for observing students' ideas and for assessing this understanding. There is some evidence that students' abilities in the laboratory are only slightly correlated with their achievement in the sciences as measured by conventional paper-and-pencil tests (Hofstein & Lunetta, 2004). These findings have suggested that students' performance, understandings, and perceptions of the science laboratory learning environment should be assessed with the use of instruments and strategies that are more closely aligned with the unique activities and goals for learning associated with the school laboratory.

In 1970, however, Grobman (1970) identified a major problem in assessing laboratory performance that persists to this day in the United States and in numerous other locations: "With few exceptions, evaluation has depended on written testing. . . . There has been little testing which requires actual performance in a real situation or in a simulated situation which approaches reality . . . to determine not whether a student can verbalize [or identify] a correct response, but whether he can perform an operation, e.g. a laboratory experiment or an analysis of a complex problem." [AQ4]

Bryce and Robertson (1985) were among several who wrote that in many countries, although students spend considerable time engaging in laboratory work, the bulk of their science assessment examines their knowledge divorced from that practical context. The hypotheses and questions students can generate from their laboratory experiences and the laboratory skills they exhibit have all too often been neglected (Van den Berg & Giddings, 1992; Tamir, 1990; Wilkenson & Ward, 1997; Yung, 2001). Gitomer and Duschl (1998) wrote that in science education, the assessment of a student's conceptual understanding has been regularly separated from the assessment of his or her procedural knowledge. They added that although discussions of performance assessment focused on laboratory inquiry skills and understanding, the limited practical assessments employed were influenced by the tradition of practical examinations; the understandings and skills examined were limited. They suggested that assessments should avoid the partitioning of curriculum experiences; curriculum, teaching, and assessment should become better integrated and holistic. The processes of science that are assessed should not be limited only to those involved in specific investigations (Millar & Driver, 1987). Gitomer and Duschl also suggested that students' prior knowledge should be assessed to assist in understanding their behavior during inquiry-type activities.

Bennett and Kennedy (2001) pointed out that because such a wide variety of goals had been articulated for science laboratory learning, it was not surprising to find disagreements in the literature about assessment methods and "what constitutes a reliable and valid assessment of practical abilities." They wrote that areas of discussion included:

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> The range and nature of the skills to be assessed;
>
> The balance between the assessment of prescriptive and investigative tasks; and
>
> The extent to which the assessment should be holistic or atomistic in its approach.

The Bennett and Kennedy project considered these issues carefully in designing a new model of practical assessment in Ireland. These issues warrant the careful consideration of all test makers, teachers, researchers who inform practice, and policy makers at a time when the assessment of science standards is playing an increasingly important role in shaping the behaviors of teachers and their students in school science. The science education community must develop and use reliable assessment instruments and strategies that are well aligned with the important goals for learning in school science classrooms in general and in laboratory inquiry in particular. The instruments and strategies must also be convenient and manageable for teachers and students, whose time, of necessity, is limited.

Although new instruments must be constructed and validated guided by goals for learning- and data-based research, instruments and strategies *were* developed in the closing decades of the twentieth century to assess the dynamics, the learning outcomes, and the effectiveness of the school science laboratory objectively. Although these strategies and resources have not been widely employed by schools and policy makers, they do offer a foundation for next steps in the research and development of assessment in science education, and they are reviewed here.

Interpreting, explaining, and reporting the results of investigations have generally been important components of student activity in the science laboratory. Students' laboratory reports and behaviors can serve as important sources of data for teachers and researchers seeking to make decisions about next steps in teaching, to assess and interpret student performance, and to assess the effects of laboratory experiences on learning. Students' laboratory reports have generally included commentary on *performance* (conducting an investigation; manipulating materials and equipment; making decisions about investigative techniques; and making, organizing, and recording observations) and *analysis and interpretation* (processing data, explaining relationships, developing findings, discussing the accuracy and limitations of data and procedures, and formulating new questions based on the investigation conducted). However, they should also include students' comments on *planning and design* (articulating questions, predicting results, formulating hypotheses to be tested, and designing experimental procedures) and *application* (making predictions about new situations, formulating hypotheses on the basis of investigative results, applying laboratory techniques to new experimental situations [Giddings, Hofstein, and Lunetta, 1991], and justifying assertions). The phases of laboratory activity (italicized above) involve more than manipulation and observation skills; they are important elements of cognitively demanding *procedural knowledge* that includes understanding and sometimes developing investigative design and developing and justifying procedures and assertions about findings. A student's *procedural knowledge* in the laboratory is interwoven with the development of that student's *conceptual knowledge* and understanding of science. Kempa (1986) was one of several who suggested that these four phases of laboratory activity—planning and design, performance, analysis and interpretation, and application—also provided a valid framework for the development and assessment of practical skills.

The Lunetta (1998) and Hofstein and Lunetta (2004) reviews provided numerous citations and discussed alternative strategies for assessing students' performance and understanding in these four broad phases of laboratory activity. The strategies included assessing written and oral evidence and performance in *practical examinations*, *laboratory reports, portfolios*, *continuous assessment,* and *combinations* of these strategies in ways that now include the use of interactive digital technology tools and resources.

*Practical examinations* can serve as valid measures of students' understanding and skill in the *performance* and *interpretation* phases of an investigation, that is, in conducting, decision-making, observing, and making inferences from their observations. As noted in earlier reviews of the laboratory assessment literature (see, for example, Hofstein & Lunetta, 2004), examples of practical examinations reported in published research studies were more visible in the 1970s and 1980s than they were at the turn of the twenty-first century. Practical examinations on some science topics have been useful for teachers and researchers and occasionally in state examinations in some countries, but their use has generally been limited to particular laboratory activities that can be administered easily to students in a restricted time, thus limiting the scope of the activities and the breadth of the assessment. Tamir et al. (1982) developed a Practical Tests Assessment Inventory to standardize the assessment of students' written responses in the inquiry-type practical examination in biology used in Israel. The 21-category inventory included categories ranging from *problem formulation* to *application of knowledge* identified in the students' investigations.

For decades, science teachers have assessed their students' performance in the laboratory via written *lab reports* completed during or after the laboratory activity. Such reports can offer important data for assessment, but when used in the ritualistic and mechanistic ways that have been so common in many classrooms, the conventional laboratory report reveals little about a student's thinking and understanding. Written evidence of students' thinking and understanding can also be gathered in paper-and-pencil tests designed to assess students' knowledge and understanding of investigative techniques and the scientific procedures, the concepts that underlie the laboratory activity, and their explanations of findings. To date, however, most assessments and grading systems have not examined students' understanding of the research design, the strengths and limitations of the procedures they used, the concepts in which the their findings are embedded, and their justifications for their findings. Although there are exceptions to this generalization, many more examples of effective laboratory inquiry assessment practices and carefully validated instruments associated with school laboratory learning are needed in the science education literature. The ritualistic and mechanistic assessment patterns that have been so deadly for meaningful learning in the science laboratory can be changed, of course. When science education research can be applied to inform the providers of high-stakes tests, those who provide support for classroom testing, and teachers, opportunities for more meaningful learning in the school laboratory can follow.

Especially in recent years, some science teachers and researchers have asked students to develop *portfolios* in which the students prepare and collect documents (increasingly using electronic media) throughout an investigation or unit or semester that capture the essence of their investigative work, their understanding, and their justification of procedures and assertions. Such portfolios can help students organize and make decisions about the best ways to report:

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what was investigated and investigative design;
procedures employed and observations;
findings and explanations;
limitations in the findings and new questions.

Portfolios can be important sources of evidence for the assessment of students' performance, activities, understandings, and explanations. Portfolios also provide data about the students' thinking that teachers can use in making decisions about next steps in their teaching in the laboratory-classroom. Progress Portfolio software (Land & Zembal-Saul, 2003) can help students organize, monitor, reflect, and interact with others on the ideas they generate throughout designing, conducting, and determining findings in an investigation. Zembal-Saul et al. (2002) reported that "while engaging in an original science investigation Progress Portfolio assisted prospective teachers in developing elaborated explanations that were grounded in evidence and . . . [in exploring] alternative hypotheses." The Progress Portfolio software was designed "to promote reflective inquiry during learning in data-rich environments." 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 (Zembal-Saul et al., 2002). Progress Portfolio is an example of software used by students in laboratory-classroom activities that can provide teachers and researchers with relatively easy electronic access to student performance data that can also contribute to the assessment of a student's development and progress. Teachers can also use that kind of information for a formative assessment to inform their teaching and their interactions with students.

In an attempt to overcome the limitations of other laboratory assessment methodologies, *continuous assessment* (Hofstein & Lunetta, 2004; Giddings et al., 1991) was designed to serve as a dynamic assessment of students' work throughout a laboratory activity. In this form of assessment the science teacher, researcher, or examiner unobtrusively observes each student during a normal laboratory session and rates him or her on the basis of a prescribed assessment protocol with defined criteria. This system was largely formalized in the United Kingdom by the Joint Matriculation Board (1979). Reflecting the contemporary position that assessment of practical work should be an integral part of the normal science course and not a separate activity, (Denby, 2004) wrote that continuous assessment of students' practical work by their teachers is now required on several occasions throughout the year in the United Kingdom; they must report the variety of practical tasks and skills students have been exhibiting in their science course. Optimally, continuous assessment provides teachers with opportunities to be more directly involved in the practical assessment of their students. However, teachers in the United Kingdom frequently treat the required laboratory assessments separately from conventional practical activities, not in the context of the normal laboratory inquiry and learning, and anecdotal evidence in the United Kingdom suggests that some students engage in very little practical work beyond what is required for their assessment. Thus, what happens in laboratory-classroom practice has often differed from the goals and visions that have been articulated for these efforts.

Science teachers have reported that assessing students during laboratory activities is quite challenging. Teachers often perceive that they do not have sufficient time or skills for evaluating when they also have multiple teaching, management, and safety responsibilities to which they must attend simultaneously (Tamir, 1989). In addition, teachers do not always believe that assessing students' performance in the laboratory should be an especially important part of science assessment. Yung (2001) wrote that teachers in his study in Hong Kong did not believe that assessment of students in the laboratory could improve their teaching and consequently their students' learning. Research examining the issues raised by Yung is needed, with larger samples of teachers in a variety of school settings to obtain more detailed information about appropriate ways to promote and sustain assessment practices that are aligned with the goals for students' learning and that can be managed successfully by teachers.

A long series of efforts have been undertaken to develop and employ multiple methods to assess students in the science laboratory and to increase the reliability and validity of those methods. Recently, Hofstein et al. (2004) used criterion-based *continuous assessment* in an *inquiry-focused* series of high school chemistry courses in Israel that included integrated laboratory activities. Teachers in the study observed individual students or groups working collaboratively. In addition, the teachers examined *hot-reports* submitted regularly by collaborating groups of students in their classes. The *hot-reports* were designed to synthesize the students' experiences, observations, analyses of data, inferences, questions, hypotheses, and plans for pursuing one or more new questions raised by their investigation. Observations of the students' performance in the laboratory, combined with assessment of the students' *hot-reports*, provided chemistry teachers with valid and wide-ranging information about their students' developing understanding and progress in the laboratory. Continuous assessment in the laboratory is now used in Israel as part of the final examination of the students in this state-approved *inquiry-focused* program. Students in the program are assessed continuously across two high school years (grades 11 and 12) on the basis of their *hot-reports* and teachers' observations of the students' performance in the laboratory. The practical assessment score, based on a performance portfolio prepared by each teacher, contributes at least 25% of each student's total final grade. It is important to note the high commitment of the state and the participating teachers to laboratory work in this project.

The project reported by Bennett and Kennedy (2001) is another showing evidence of a high commitment to laboratory work by the state, in this case in Ireland, and participating teachers. Their study was designed to "evaluate the effectiveness of a new assessment model for practical work." It involved 700 students and 30 schools in Ireland and compared students' written and practical performance associated with their laboratory work in physics and chemistry. Bennett and Kennedy reported that the model developed in their project "provided a reliable and valid assessment of a range of practical abilities, which was also economical of time and resources. Additionally, there was evidence of benefits to the examiners and teachers in terms of their own professional development." [AQ5] Given the substantial commitment of the state and the participating teachers to laboratory work in both the Irish and Israeli projects, it will be important to examine the effects of that commitment on long-term teacher and student behaviors and on multiple issues associated with the nature of the related science learning in years to come.

As noted earlier, limited research has focused on the complex but potentially important intersections between students' understanding of the *nature of science*, how that understanding may influence students' observations and findings in laboratory work, and how the students' understanding of the nature of science may be influenced by laboratory experiences. To develop the knowledge needed to guide relevant curriculum development and teaching decisions, it is important for researchers and teachers to have valid, reliable, and convenient measures of students' understanding of aspects of the nature of science that intersect with practical work in the laboratory. A review of nature of science instruments and associated issues is included in Chapter 29 of this *Handbook*. As noted in that chapter, assessment instruments of this kind are very difficult to develop. However, the task can be accomplished with collaboration among people with expertise in psychometrics, science education, and the philosophy, history, and sociology of science, when the need for the task is understood and supported by the constituencies involved. Research and development conducted by Fraser and a series of colleagues (Fraser, 1998) resulted in the development of the Science Laboratory Environment Inventory (SLEI), discussed earlier in this section and in Chapter 6 of this *Handbook*. Such research is also needed to serve as a foundation for developing assessment protocols that intersect the affective and cognitive domains. Once again, although busy researchers and teachers can use existing resources and strategies to assess students' *conceptual and procedural knowledge, understanding of the nature of science, and attitudes* associated with *laboratory* learning, the development and use of valid, reliable, and convenient assessment instruments and strategies is a very important area for further discipline-focused research in science education that will guide teaching practice and education policy.

## THE SCHOOL LABORATORY: IMPLICATIONS FOR CLASSROOM PRACTICE AND RESEARCH

In *The End of Education*, Postman (1995) wrote that efforts to improve schooling require attention to the *means* for educating children, but that the "reasons" or *ends* for learning and schooling are far more important. Compelling abstract, metaphysical ends provide meaning and significantly influence education and schooling. However, practical guidance is also needed in shaping both school science reform efforts and moment-to-moment teaching decisions in the science classroom and laboratory. The bulleted goals for learning in the school science laboratory shown in Table 15.1 and discussed earlier in this chapter are important but broad. To guide teachers' pedagogical decisions and thus to improve learning in complex, busy school laboratory settings, curriculum developers and teachers need to develop more detailed objectives derived from the broader goals; more explicit objectives will also provide guidance that helps students understand the purpose for specific activities and what they need to do consistent with those purposes. Relevant research on laboratory-classroom learning can inform the development of such objectives and teaching strategies.

### Selecting and Promoting Learning Goals for Focused Learning in Specific Laboratory Experiences

Education goal statements in contemporary science education reform documents such as *Project 2061: Science for All Americans* (AAAS 1989), *the National Science Education Standards* (NRC, 1996), and international standards documents reflect the broad goals discussed earlier in this chapter. These goals are best implemented in ways that are particularly relevant to local needs and resources. To these ends, more focused goals for science laboratory learning such as those shown in Table 15.2

**TABLE 15.2**
**More Focused Goals for Student Learning in the School Laboratory**

| |
|---|
| Identify problems for inquiry, suggest strategies for that inquiry, and successfully solve laboratory problems |
| Participate actively in working toward specific understanding and solutions |
| Exhibit creativity and curiosity in science inquiry |
| Exhibit interest and an internal locus of control in science inquiry |
| Communicate and collaborate in science inquiry |
| Set goals, make decisions, exhibit analytical and reflective thinking, and self-evaluate while inquiring and investigating |
| Retrieve and use current scientific concepts during authentic inquiry |
| Demonstrate an understanding of the nature of science and its relevance for investigative design, interpreting data, and formulating findings |
| Make and justify decisions regarding the methodology, data collection, analysis, scientific claims, organization, and presentation of laboratory work |
| Demonstrate robust understanding of fundamental science concepts (*not* simply articulating isolated facts and using mathematical algorithms to solve relatively meaningless problems) |

should be articulated. Promoting these more focused but still general learning outcomes demands that teachers, curriculum developers, and researchers consider how particular laboratory experiences can promote more explicit, age-appropriate, science learning objectives. They must articulate relevant objectives consistent with desired goals for learning and unique opportunities within specific laboratory activities to guide teachers' and students' decisions and behaviors. Subsequently, the success of laboratory experiences should be examined by the assessment of students' learning associated with the explicit objectives. Decisions regarding selection of laboratory activities and materials, adjustments in the curriculum, and appropriate teacher behaviors and strategies should be influenced by the information gathered from assessments targeted to explicitly stated objectives for student learning in the school laboratory.

## Selecting and Scaffolding Topics, Ideas, and Laboratory Activities Appropriate for Concept Development

Important science concepts should be revisited throughout a science course in different and more complex laboratory contexts. Within a course, the selection and sequencing of topics and concepts for student investigation are factors that influence effective teachers' decisions on the selection and use of laboratory investigations. With more deliberate sequential course design and sensitive scaffolding of concepts, students can be encouraged to make more connections between concepts, materials, and contexts. Information about the students' relevant prior knowledge and skills as well as about their ability to handle abstractions, multiple variables, and alternative representations are important factors in the day-to-day decisions of effective teachers. As discussed in the *learning empowering technologies* section of this chapter, this very important area for research and development in science education has led to the production early in the twenty-first century of potentially very helpful software tools designed to support inquiry and the depth and stability of students' concepts and their networks of concepts. These tools should be used with students, and their effectiveness in promoting learning in the laboratory-classroom should be studied very carefully.

To promote conceptual and procedural understanding and engagement, particular laboratory activities must be selected for more thorough investigation in which students experience meaningful inquiry in a time frame that makes sense within the constraints of a school science course. Because in-depth, conceptually focused laboratory study usually consumes considerable time and classroom-laboratory time is of necessity limited, some laboratory activities should be selected for in-depth attention while others are treated less intensively. To conduct those activities effectively, other, less crucial school laboratory activities must be bypassed in favor of more time-efficient alternatives to laboratory teaching, such as simulations and teacher-mediated demonstrations. Many science topics are not readily amenable to first-hand examination in the school laboratory because the materials involved are dangerous to manipulate, very expensive, too large, or too small for students to examine first hand; other important phenomena may take place across time frames that are far too long or too brief to examine in real time (Lunetta & Hofstein, 1991). In deciding what science content is deserving of thorough investigation with materials in the laboratory and what content may be treated with more limited hands-on experiences, the following questions should be carefully considered:

> What are the principal learning outcomes sought for students in an investigation? Which laboratory activities can successfully promote important learning outcomes, particularly those most neglected in other school science experiences?
>
> To what extent is the science content in the laboratory experience (including nature of science issues) crucial for scientific literacy? To what extent does that content warrant in-depth investigation when compared with other important content?
>
> To what extent is the content in the laboratory experience fundamental to one or more science disciplines and extensively linked to other important science concepts? (Content that is well linked to several other important science concepts should normally have higher priority for in-depth investigation.)
>
> To what extent is the science content difficult to comprehend without concrete experiences that can be used to challenge and extend students' thinking?
>
> To what extent can students develop meaningful understanding of the important concepts and ideas through a mentally engaging demonstration or simulation, rather than in a more time-consuming, hands-on investigation with materials?
>
> To what extent are students likely to follow directions relatively mindlessly in pursuing the stated objectives?

AU:
bullet list
wanted?

In general, science knowledge (conceptual and procedural) that is central in science literacy, fundamental to one or more science disciplines, and difficult to understand without extensive hands-on and minds-on experience deserves in-depth laboratory investigation. On the other hand, "cookbook" verification activities and laboratory experiences that can be taught effectively through teacher-mediated demonstrations, appropriate simulations, and other alternative practical modes of learning and teaching are good candidates for alternative treatment or even for elimination in a conventional laboratory format. Well-conducted, mentally engaging demonstrations and simulations can often be effective and time-efficient, particularly if teachers pose effective questions and scenarios that interest and engage students cognitively. Although the learning outcomes will not be identical, demonstrations can be very appropriate and efficient alternatives to laboratory activities, especially when the instrumentation available for the laboratory normally introduces large measurement error, when special technical expertise is needed to operate those instruments successfully, or when conducting the laboratory activity successfully necessitates particularly heavy commitments of time.

## Selecting Laboratory Materials to Match Goals for Learning with Students' Needs

The materials selected for use in a particular investigation often play a very important though complex role in promoting or confounding what students observe and learn. The simplicity or complexity and the novelty or familiarity of the materials and technologies to be used in the laboratory are among the important variables that teachers and curriculum developers must consider to promote meaningful learning. Using equipment and materials that students experience regularly in the world around them in laboratory investigations can help the students to understand and apply what they are learning in the laboratory. It is important to note, however, that students often bring long-standing misconceptions about the nature of familiar materials with them to school science. These misconceptions can interfere with the ways a student thinks about the materials or equipment, their functioning, and their roles as objects of investigation or as tools in the laboratory. Such misconceptions can influence students' expectations, observations, and understanding of the phenomena they are studying, as illustrated earlier in this chapter when a student's failure to understand the design and purpose of a simple light bulb socket interfered seriously with her ability to interpret a simple electric circuit. Equipment that is novel and not part of a students' prior experience can also influence their learning in the laboratory (Olson & Clough, 2001). When visitors first enter informal environments (a museum, for example), they spend substantial time becoming familiar with that environment before engaging with the exhibits (Falk & Balling, 1982; Kubota & Olstad, 1991). Similarly, when students encounter novel materials during laboratory activity, their attention focuses first on the nature of the novel materials and their functioning Olson (2004). As a result, the students may not focus on important science concepts that the teacher had intended to be a priority. When physics students use a graphing software tool for the first time, for example, their attention may be drawn to the procedures involved in using the software rather than to the graphical representations of the relationships and the concepts the graphing software was intended to illustrate and help them understand. This is but one example of the kind of issue that warrants empirical research to inform good teaching practice.

Johnstone and Wham (1982) wrote that laboratory investigations often overload students with too many variables and too much information to process, whereas Gunstone and Champagne (1990) reported that laboratory work could successfully promote conceptual change, especially if the activities focused on careful treatment of limited *qualitative* tasks. So focusing attention on describing relationships between principal variables and patterns observed in an investigation without the need to attend to multitudes of other details in an investigation can facilitate conceptual understanding at times. When materials are selected to use in laboratory activities, consideration must be given not only to the objectives articulated for students' learning, but also to their prior knowledge and understandings. Therefore, teachers need to help students verbalize their ideas, not only about the relevant science concepts, but also about the nature and function of the laboratory materials to be used in investigating their research questions. Questions that science teachers ask in the laboratory and those they ask students to address in their *portfolios* or *lab reports* can help teachers as well as students to comprehend and explain the investigative procedures and materials used, issues linked to the nature of science, and their understanding of relevant science concepts. With this information, teachers will be in a much better position to select and modify laboratory objectives and activities and to employ more sensitive teaching strategies.

### Selecting and Modifying Activities to Encourage "Minds-on" Engagement in the Laboratory

As noted throughout this chapter, goals for learning in science education and knowledge of how people learn should guide teachers in selecting and modifying laboratory activities to promote those goals and the more explicit objectives derived from them. When possible, science laboratory activities should encourage students to exhibit the behaviors outlined in Table 15.3. Student behaviors like these can engage students in more meaningful laboratory activities. They are advocated in numerous papers informed by research on learning, and they can be useful for teachers in restructuring their laboratory activities to become more congruent with what we know about learning and goals for student learning. Researchers investigating school science laboratory experiences need to report the extent to which the laboratory activities and teacher-classroom environment engage students in these kinds of decision-making experiences and the effects on learning outcomes for the students.

Multiple studies confirm that the frequently observed ritualistic, even "mindless" student behaviors observed in many laboratory activities stifle students' personal engagement in decision-making in the laboratory. These kinds of activity

**TABLE 15.3**
**Student Behaviors to Encourage in Particular Laboratory Activities**

Effective laboratory activities encourage students to

1. Explicate the principal question(s) they are investigating
2. Explicate their relevant prior knowledge, e.g., predict outcomes and provide reasoning
3. Employ previously studied science ideas in more complex ways, e.g., determine the products of a chemical reaction with the use of chemical nomenclature, chemical and physical properties, and stoichiometry
4. Invent laboratory procedures. When this is not possible, students should be asked to explain the rationale for steps in the prescribed procedure.
5. Decide what data is relevant and irrelevant; explain what the data means. When students struggle to do this, teachers should ask questions that help the students make progress without making decisions for them.
6. Apply mathematical reasoning to problems. When students are told precisely when and how to use mathematical algorithms to process their laboratory data, then they are unlikely to think conceptually about what they are doing.
7. Set goals, make decisions, and assess progress. Rather than answering all student questions, teachers ask students to explain what they are attempting to do, the procedure they used, what data they collected or are attempting to collect, what meaning they are making from their data, and the reasons for their assertions.
8. Communicate their laboratory work in a clear manner. Rather than prescribe a written laboratory report or portfolio format, have small group and/or class discussions in which the students decide how best to organize and present their research questions, methods, data, interpretations, findings, and new questions. The discussion should include pros and cons of various approaches.
9. Discuss limitations in their sampling, measurement, and data
10. Make connections between science concepts and everyday phenomena. Ask questions that help students observe these relationships
11. Raise new questions suggested by their investigations
12. Reflect on the nature of science. Raise questions that have students consider fundamental assumptions underlying their laboratory work: how theory guided the design and procedures used and their interpretations of data; the role of creativity and ingenuity in their laboratory investigations

*Note:* Adapted from Clough (2002).

rarely uncover students' underlying beliefs; they do not encourage students to wrestle with their prior knowledge in making sense of their experiences, and they do not encourage them to reflect on their own thinking. The selection of laboratory activities that actively encourage students to wrestle with science concepts (and hence to better understand them) is one of several important and complex matters. Laboratory activities should be aligned with desired goals for learning, be within learners' zones of proximal development, and require active student engagement. When laboratory activities are outside a student's zone of proximal development, the student has little choice but to follow directions blindly, and the time invested in the laboratory activity is likely to result in learning that is far from the desired goals articulated at the outset.

Laboratory activities that engage the mind as well as the hands have students "thinking out loud, developing alternative explanations, interpreting data, participating in" constructive argumentation about phenomena, developing alternative hypotheses, designing further experiments to test alternative hypotheses, and selecting plausible hypotheses from among competing explanations (Saunders, 1992, p. 140). Students' thinking should be expressed openly and discussed to help students act on their underlying beliefs in the context of alternative explanations; the articulation of students' ideas can also enable teachers to understand and hence to help the students develop deep, scientific conceptual understanding. Because teachers have limited time to interact with all students in a laboratory class, having the students use appropriate electronic tools like Progress Portfolio while conducting their inquiry can assist in facilitating the deep understanding that is consistent with goals for learning. Again, here is an area of contemporary research on science teaching and learning that warrants careful study.

## Selecting Models and Strategies to Guide Laboratory Teaching

The reviews of the school laboratory literature discussed earlier reported a mismatch between the goals articulated for the school science laboratory and what teachers and students regularly do in laboratory activities. Ensuring that students' experiences in the laboratory are aligned with stated goals for learning demands that teachers explicitly link decisions regarding laboratory topics, activities, materials, and *teaching strategies* to desired outcomes for students' learning. Effective laboratory activities require significant student engagement, thinking, and decision-making, but teachers play a crucial role in helping students have productive experiences. The teaching models and strategies teachers employ to guide their behaviors in the laboratory-classroom and the ways in which they interact with students influence the extent to which well-designed laboratory activities promote desired learning. The *learning cycle* and subsequent teaching models were designed to guide teaching that promotes learning.

*Search, Solve, Create, and Share* (*SSCS*) is a relatively open-ended teaching model (Pizzini et al., 1989) that is well suited for school science laboratory experiences. During the *search* phase, students take part in identifying researchable questions and then in refining them. In the *solve* phase, students in small cooperative groups consider ways to investigate their research questions, using procedures they have developed. In the *create* phase, the groups prepare their presentations, reporting their research questions, investigative work, results, and conclusions. Each group's presentation is shared in the final *share* phase of the strategy. Pizzini and Shepardson (1992) compared classroom dynamics in a traditional laboratory with that in a SSCS setting. They reported that in the traditional laboratory setting student behavior appeared not to be influenced by the design of the laboratory experience, whereas in the SSCS setting "student behaviors are exhibited in response to . . . the lesson structure—designing a research plan, collecting data, analyzing data, and evaluating" (p. 255). The SSCS teaching strategy helped students learn to ask researchable questions, to design a research plan, and to answer some of those questions. Whereas many teaching strategies encourage students to ask and investigate questions, some strategies like SSCS place greater direct emphasis on expecting these behaviors.

Combining different elements of recommended teaching models can help individual teachers engage students in wrestling with the meaning of laboratory observations. For instance, the *Science Writing Heuristic* (*SWH*) (Keys et al., 1999) can be effective in promoting thinking, negotiating meaning, and writing about science laboratory activities. The SWH strategy can be integrated with learning cycle approaches and with an SSCS problem-solving approach. The SWH strategy can help students move beyond traditional school science laboratory reports, toward more personal, expressive forms of writing while improving their science understanding (Rivard, 1994). The SWH strategy guides teachers and their students in thinking and writing, and it encourages students to elaborate the links between claims and evidence. An SWH template guides teachers in helping students to negotiate meaning with small groups and with the entire class. A student template incorporates scaffolding questions that form the heuristic: What is the question being investigated? What did I do? What did I see? What can I claim? What is my evidence? What do others say? and How have my ideas changed? These prompts encourage metacognitive behaviors consistent with how people learn and promote many goals articulated for school science laboratory activities. For instance, in a study with grade 6 students, those engaged in the SWH strategy demonstrated higher order cognitive operations when completing laboratory activities, compared with those using a more traditional laboratory report format (Grimberg et al., 2004). Effective implementation of the SWH has been shown to improve grade 7 students' performance on conceptual essay questions focusing on the big ideas of a topic (Hand et al., 2004). Similar results were obtained for freshman university chemistry students' performance on conceptual essay questions and the American Chemical Society semester 1 examination (Rudd et al., 2001; Burke et al., 2003). Based on semester final examinations, the project reported success when the SWH strategy had been used in the lectures of a university chemistry course.

*Predict-observe-explain* (*POE*) and *think-pair-share* (*TPS*) are examples of other teaching strategies that can be used effectively alone or in combination with teaching models described earlier to elicit students' thinking and promote minds-on, not just hands-on engagement in school science laboratory experiences. Both POE (White & Gunstone, 1992) and TPS engage students in thinking about a laboratory phenomenon and sharing their thoughts with their classmates and the teacher. POE can be used with an entire class, small groups, or individual students. Having students make a prediction often raises interest in what will be observed and investigated, and in the process, teachers can gain important insight into students' thinking (Liew & Treagust, 1995; Palmer, 1995). When observations do not match students' predictions, cognitive conflict and motivation for learning may ensue. Whether or not students' predictions match what they observe, the most important step of this strategy is the explanation the students provide for their predictions and how they account for observations that deviate from what they had predicted. TPS can be used in small groups and with the entire class when a teacher wants students to contemplate a question or phenomenon individually, then interact with other students to discuss their ideas, and finally share what they think with the teacher, group, or entire class.

A questioning strategy proposed by Penick, Crow, and Bonnstetter (1996) is well suited to school science laboratory investigations because it reminds teachers to determine explicitly what students have done and to help the students recall and use those experiences to speculate, build relationships, create explanations, and apply knowledge. The strategy can be particularly useful to teachers as they work to change their own roles and behaviors during laboratory activities, and it can guide researchers in describing the nature of student and teacher behaviors that may be related to learning outcomes. The examples shown in Table 15.4, while not an invariant step-by-step progression of questions, illustrate how the strategy is useful in the laboratory to ground questions in what students have done and to help the students bridge to more abstract concepts. Even well-written laboratory activities may not enable students to learn with the deep understanding intended by their designers when they are poorly implemented in school settings. Selecting and implementing appropriate teaching strategies can have a powerful influence on the

**TABLE 15.4**
**Questioning Strategy for School Science Laboratory Experiences**

*History*—Questions that relate to students' experience:
  What did you do . . .?
  What happened when you . . .?

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

*Application*—Questions that require students to use knowledge in new contexts:
  How can this idea be used to design . . .?
  What evidence do we have that supports . . .?

*Speculation*—Questions that require thinking beyond given information:
  What would happen if you changed . . .?
  What might the next appropriate step be?

*Explanation*—Questions directed to underlying reasons, processes, and mechanisms:
  How can we account for . . .?
  What justification can be provided for . . .?

*Note:* Adapted from Penick, Crow, and Bonnstetter (1996).

extent to which learning outcomes sought for students are achieved. In addition, examining the effects of specific teaching strategies and models on student learning should be an important goal for focused research that can inform practice in science education. These are very important tasks not only for science education researchers per se, but also for science teachers and science teacher education.

## ROLE OF THE TEACHER DURING LABORATORY ACTIVITIES

As noted earlier in this chapter, contemporary science concepts rarely emerge from school laboratory experiences and data unless the students have thoughtful conversations with an informed teacher who can help them contrast their ideas with those of the scientific community. Gunstone and Champagne (1990) noted that the need for meaningful interaction and reflection in the laboratory is essentially a call for discussion, "a teaching strategy which has been widely under-used in laboratories" (p. 179).

Windschitl (2002) wrote that "Supporting student learning . . . requires special skills and conditions" (p. 145). These teaching skills are especially important when teachers work with students in the laboratory, and researchers investigating school laboratory experiences should examine and report these "skills and conditions" with special care. Laboratory activities create many opportunities in which the students can describe: what they *see*, what they are *doing*, and how they *explain* these things. Yet, asking thought-provoking questions that help students to articulate their observations, their inferences, and their explanations and to connect these with science concepts they "know" and with the concepts of experts is a particularly important and challenging task for a teacher (Driver, 1995).

Effective teachers encourage students to share their thinking by asking effective questions with appropriate wait time I and II (Rowe, 1974, 1986), carefully listening to students' ideas and asking for elaboration, acknowledging those ideas without expressing judgment, and responding with further questions and ideas that are based upon the students' comments. These skills and other complementary teacher behaviors can create mentally engaging and productive laboratory discussions conducive to meaningful science learning. These behaviors are essential *tools* that teachers use to understand students' thinking during laboratory activities and to help students piece together desired understandings. The importance of these behaviors, especially in the school laboratory, suggests that effective teaching is far more complex and challenging than most observers and even many teachers believe it to be (Clough, 2003; Windschitl, 2002).

This complexity and challenge is illustrated in a short transcript from a case study report adapted from Clough (2003) and shown in Box 15.1. The example illustrates the critical role teachers can play in learning and the importance of the pedagogical practices they use in teaching. The laboratory activity that was the context for Box 15.1 might be perceived by a layperson as simple *hands-on* learning, but to an informed teacher who is sensitive to the nuances of learning and teaching, the learning interactions visible in the dialogue are complex. A careful reading of Box 15.1 shows an expert teacher who worked to understand students' thinking, challenge misconceptions, and help the student make links to science concepts that led

## Narrative Box 15–1

## One Example of the Teacher's Crucial Role in the Laboratory

Dan was a "good student" who along with his classmates had successfully completed a learning cycle sequence exploring characteristics of chemical change including the conservation of mass several weeks prior to the dialogue below. In that activity, students improved their experimental design several times to prevent escape of the gas produced. With each sequential improvement the "loss" of mass resulting from gas leaking out of the system became smaller. Through these experiences, students came to the conclusion that under perfect conditions (i.e., no substances are lost or gained by the system, perfect balance, etc.) that mass would remain exactly the same before and after a chemical reaction. Dan had appeared to understand a series of activities and discussions that had taken place in the following weeks including balancing chemical reactions, the mole concept, and stoichiometry. Later, the students were enthusiastically attempting to determine the products of that prior chemical reaction using all that they had learned during the entire year in chemistry. Several days into this activity, Dan approached his teacher and the following conversation ensued:

Dan: "Mr. Smith, the mass of my system went down."

Teacher: "How do you account for that, Dan?"

Dan: "A gas was formed and gases have no mass."

Teacher: (Inwardly surprised, but maintaining an accepting and inquisitive outward appearance) "What do you think gases consist of?"

Dan: "Atoms."

Teacher: "What do you know about atoms and mass?"

Dan: "Atoms have no mass."

Teacher: (Doubly surprised and searching for a way to help Dan see his misunderstanding) "Dan, what are you made up of?"

Dan: "Atoms." (Pause, followed by a paradoxical look on his face.) "And I have mass."

In the episode, the teacher kept in mind the overarching goals he had for the students. The teacher's response to Dan reflected an understanding of how people learn and how they often struggle to fully comprehend what the teacher has in mind. To help Dan develop a more scientifically accurate concept, the teacher did not tell Dan how to interpret the data. Instead, he posed a question to have Dan elaborate on his statement. Using non-judgmental, but encouraging nonverbals, the teacher waited again (wait-time II). The teacher's hard won interaction pattern provided Dan with more time to think and talk, while giving the teacher more time to consider what his next move would be. Using positive voice-inflection with a line of questioning he thought would resolve the issue, the teacher continued the interaction while listening intently to Dan's thinking, acknowledging his ideas without judging them, and responding with questions developed from what Dan had said. The teacher reported that while Dan was telling him that *atoms have no mass*, the periodic table of elements was visible to Dan. On it, the atomic masses were clearly displayed, and they were numbers Dan had used consistently in solving stoichiometry problems. Some of those problems had explicitly addressed the mass of reactants and products in the gaseous state, and Dan had solved them successfully.

to more meaningful and comprehensive scientific understanding. Worth noting again is the need for research on learning in the school laboratory that recognizes intricate and intertwined teacher and student behaviors and more clearly articulates the roles of the teacher in promoting meaningful interaction and reflection in the development of more scientific ideas and understanding.

## TOWARD APPROPRIATE QUESTIONS, METHODS, AND ASSESSMENT SCHEMES IN LABORATORY-RELATED RESEARCH IN SCIENCE EDUCATION

"At its core, scientific inquiry is the same in all fields. . . . Research . . . is a continual process of rigorous reasonings supported by a dynamic interplay among methods, theories, and findings. It builds understanding in the form of models or theories that can be tested" (Shavelson & Towne, 2003, p. 2). Unfortunately, careful scholarship and student performance data have *not* consistently driven the policies and practices associated with teaching in the school science laboratory. Our review of the literature fails to show many empirical studies that have investigated carefully the causal effects of the objectives, laboratory instructions, teaching models, and teaching behaviors experienced by students in the laboratory on the attainment of explicit objectives for learning articulated for particular laboratory activities or on the broader goals for learning articulated in contemporary science standards. Reviews in past decades have reported disappointment with studies on the laboratory, resulting from (a) failure to explicate goals and objectives for laboratory activities; (b) assessment instruments that were not well aligned with the goals of laboratory work; (c) mistaken notions regarding the nature of science; (d) failure to delineate what the teacher and students were and were not doing before, during, and after laboratory experiences; and (e) other factors discussed in this chapter. Although progress has been made, many of these problems have not been properly addressed. The laboratory presents many opportunities for promoting desired learning outcomes, but what we know about learning and effective teaching has not been visible regularly in many school laboratory settings.

Many variables interact to influence student achievement and attitudes, and searching for single cause-effect relationships in teaching and learning associated with the laboratory is contrary to the complexity that we have come to know is inherent in meaningful science teaching for human learners. Thus, employing research designs that can examine and link complex laboratory-classroom variables to learning outcomes will be a challenging but important goal. To inform practice more optimally, next steps in research on the school science laboratory should include studies that examine multiple interacting variables and research questions to ascertain the nature of their individual and composite effects on students' science learning. Research on the laboratory in school science should examine the important interacting roles of students' prior understanding of relevant conceptual and procedural knowledge, students' understanding of the nature of science, and their understanding and comfort with laboratory technologies, perceived goals and objectives articulated for laboratory learning, the roles played by curriculum materials, teachers' interactions with students, laboratory assessment systems, the teachers' scientific and pedagogical knowledge, and other relevant variables. Ultimately, the science education community should have much more *scientific* information about the nature of the individual and composite effects of these variables on students' science learning to better inform teaching practice and education policy. There is much work to be done.

Research on the school laboratory should also examine some of the very important social and ethical issues that influence teachers' decisions to engage or not to engage their students in laboratory activities. Two examples of important issues that have not been examined and discussed substantively in the literature are concerns about *laboratory safety* and about *valuing living* (*or formerly living*) materials. Busy teachers who are concerned about promoting humane and scientific habits of mind, values, and inquiry as well as safety must function within schools in which many administrators today are particularly concerned about avoiding potential controversy and litigation while operating with limited budgets. Teachers who are concerned about promoting inquiry as well as the valuing of living things must make decisions about activities to be included or avoided in science laboratory-classrooms. These decisions are made within an array of community values (antivivisection and immature student behavior among them) that influence those decisions. Meaningful research that can inform practice and policy must examine these kinds of issues as well as those in the domain of students' cognition.

One important part of the task is to identify appropriate research designs that can guide next steps in organizing research studies. Research questions, methodologies, and assessment instruments must be aligned in response to the problems and issues discussed in this chapter. Many studies have been conducted with the use of case-study methodologies that have provided information about effects of practices on learning in school laboratory settings. These initial steps have been informative, but it has been difficult to generalize beyond the small samples that were studied. More systematic research, sometimes with complex research designs, is warranted to yield more generalizable findings. The structure and size of many secondary and university science laboratory courses (often with multiple sections) make treatment/control research designs possible. In cases where a large number of students are enrolled, such as in college science courses, *Solomon four-group designs* (Isaac & Michael, 1987) may be appropriate, for example. Structural Equation Modeling (Gall et al., 1996; Hoyle, 1995) and other complex designs might better help science education researchers understand the role of the laboratory in conjunction with other aspects of effective teaching; contemporary social science research designs should be explored and employed. Meta-analytic studies could also provide insight into the effects of specific kinds of laboratory treatments and experiences.

Organizing for larger-scale and longer-term studies of the kind recommended here requires not only the broader expertise that is possible in well-constituted collaborating teams of researchers, but also structures for research that go beyond one classroom and teacher, beyond a single school or community, and beyond classical university science and education departments. Creating and supporting the development of competent, collaborative researchers, research teams, and larger institutional structures sensitive to school and teacher, research and development issues will be challenging. Nevertheless, these are very important tasks en route to conducting research that will properly inform and improve education practice and policy.

## FOUNDATIONS FOR THE TWENTY-FIRST CENTURY: LOOKING TO THE FUTURE

In this chapter, we have reviewed and synthesized multiple activities that have fit within a definition of the school *laboratory* derived from the science education literature and articulated in the introduction to this chapter. *Laboratory activities* have been used in multiple natural science disciplines to teach students of multiple age spans in very different cultural and classroom contexts. In the many studies and varied research settings, important issues and variables intersect. However, there have been many substantive differences in the laboratory settings and in other variables reported. To develop research in the field, the science education community and especially the research community must be careful to explicate detailed descriptions of the participating students, teachers, classrooms, and curriculum contexts in research reports. Among the many variables to be reported carefully are learning objectives; the nature of the instructions provided by the teacher and the laboratory guide (printed and/or electronic and/or oral); materials and equipment available for use in the laboratory investigation; the nature of the activities and the student-student and teacher-student interactions during the laboratory work; the students' and teachers' perceptions of how the students' performance is to be assessed; students' laboratory reports; and the preparation, attitudes, knowledge, and behaviors of the teachers. What do the students perceive they are supposed to accomplish in the laboratory activity? How do they perceive their laboratory performance will be assessed? How important do the students and the teachers perceive the laboratory activities to be? Studies should clearly report the amounts of time students spend in laboratory activities and how those are integrated or separated from other work in the science course. They should distinguish clearly between long-term and short-term student investigations and indicate clearly the numbers and roles of students in each laboratory team. Because substantial differences often are present in different laboratory settings, detailed descriptions of the subjects and contextual details are especially important. To support the development of knowledge that can advance science education by informing curriculum development, teaching and assessment practices, and education policy, it is essential to define technical terms precisely to explicate knowledge in the field; it is also important to use those terms consistently in research reports and in scholarly writing.

In the introduction to this chapter, we articulated a classical definition of school science laboratory activities that would have been appropriate in the nineteenth century and most of the twentieth. We wrote that laboratory activities were learning experiences in which students interact with materials or secondary sources of data to observe and understand the natural world. We also wrote that the increasingly widespread use of digital computing technologies in school science near the turn of the twenty-first century offered not only new tools for gathering, visualizing, and reporting data, but also important simulation resources for teaching and learning science. We have written that work with simulations has helped us to understand that school laboratory activities are themselves simulations of some of the things that scientists do. To teach meaningful science successfully, teachers' decisions must be informed by substantive research on these complex issues. Because citizens in a high-technology society need to understand the important distinctions between real and virtual realities or worlds, that is one more learning outcome that will come to be expected of science education early in the twenty-first century. Experiences with real and virtual materials in school science have important roles to play in developing the needed understanding.

Early in the twenty-first century, young people in high-technology societies are immersed in virtual experiences in increasingly endemic digital/video games, and they move between real and virtual realities, frequently without noticing the transitions. The distinction between real and virtual tools and phenomena is one more complex and important variable that science teachers in the twenty-first century must consider to promote scientific understanding. The powerful new electronic tools and resources blur the interface between learning in the laboratory with real materials and learning with simulations that are representations of nature. We predict that before long a new goal/standard will emerge as an expectation for science education, that is, *school graduates will discriminate between real and virtual realities*. The school laboratory will have a very important role in the teaching and learning associated with this outcome.

In the twenty-first century, students will increasingly move between real and virtual realities in their science classes. On some occasions they will process and graphically display laboratory data gathered from the study of real materials, and on other occasions they will process and graphically display data generated by electronic simulations driven by models that have been created by others or by the students themselves. We have reported evidence in the chapter that digital tools in the laboratory at times can help students visualize and understand science concepts, whereas at other times they can seriously confound understanding. Curriculum developers and teachers need to be well informed about these important issues in teaching and learning, and new research is warranted to provide the information needed. The new electronic tools associated with the school science laboratory offer important opportunities for teaching and learning in science; they also offer important opportunities for the scholarly study of learning, students' understanding, and the experiences and teaching prompts that support the development of scientific understanding. For these reasons, the need has arisen for a *new* definition of the school science laboratory that will encompass the simulation of natural phenomena and be appropriate for science education in the twenty-first century.

From a 50-year perspective, considerable progress has been made in the articulation of carefully conceptualized goals for science learning and in what we know about the learning of science. Many now recognize that science curriculum development, science teaching practices, and science education policy should be guided by those goals and by that knowledge. Curriculum development and teaching methodologies reflecting theories of how people learn have begun to be tested on the basis of student performance data, but these research and development activities are not sufficient, given the need to improve education in science and the magnitude of current problems. To achieve what is needed, research and development on these important issues in science education must accelerate.

Science education scholarship to date does provide a foundation for movement toward theories and research that can guide the development of curricula and teaching practices in science education and in the laboratory. Much evidence suggests that carefully conceptualized and carefully delivered laboratory activities are very effective in helping students develop and apply science concepts and procedural knowledge. However, research results have been difficult to interpret because central goals for learning in the laboratory, assessment measures, and research methodologies have not been well aligned. Contemporary social science research designs must be used to examine complex laboratory-classroom events and an array of variables that are well grounded in theories of science learning and the extant scholarship. To examine the matrix of interacting variables, collaborative research conducted by teams of persons who bring together knowledge and skills in science education, science, and appropriate education research methodologies is warranted.

At the beginning of the twenty-first century high-stakes tests in the United States and elsewhere increasingly drive what school and state administrators, parents, teachers, and students think is important in school science. Because there is a concurrent, widespread perception that what those tests measure is not well linked with time spent on activities in the school laboratory, to expect that students' and teachers' behaviors will shift toward more effective laboratory practices is naïve unless the perceptions change. Significant discrepancies exist between what we know about learning science and current science teaching practices and policy. The policy makers who control the testing programs and those who prepare the tests must become an integral part of more functional efforts to improve the effectiveness of school science.

What we know about science learning and the goals for science learning must be reflected in the science standards, and the standards must be linked to the development of valid and reliable tests. Most assessment of students' understanding and performance in the school laboratory continues to be confined to limited, conventional measures at best. Thus, substantial research and development is needed to create more valid, comprehensive, and useful measures of students' understanding of laboratory *procedural knowledge* and its intersections with the development of students' *science concepts*, their understanding of *the nature of science*, and their *attitudes toward science and the school laboratory*; the results of those efforts must be applied in science teaching practices and policy.

Although many questions about effective school science laboratory experiences remain to be answered, this chapter makes clear that much has been learned about the teaching, curriculum, and laboratory learning environments that promote desired science education goals. This knowledge provides a foundation for research that can inform teaching and curriculum practices and science education policy. The review of literature in this chapter also illustrates the very important and complex nature of teaching in the school science laboratory. Contemporary developments in understanding the nature of science are likely analogous, in part, to contemporary developments in understanding the effects of complex science classroom events on science learning. Overarching claims (pro or con) about the value of school science laboratory experiences are misplaced as myriad variables influence learning outcomes. These interacting variables must be examined carefully to better understand the potential and realities of laboratory experiences.

Much must be done to assist teachers in engaging their students in school science laboratory experiences in ways that optimize the potential of laboratory activities as a unique and crucial medium that promotes the learning of science concepts and procedures, the nature of science, and other important goals in science education. Science education researchers, teachers, curriculum developers, administrators, and policy makers all have important roles to play in these efforts. Understanding and advancing science education learning and teaching, promoting the development of science curricula, and supporting the development of effective science teachers are very complex activities, and simplistic solutions will be naïve and inadequate. Those important activities must continually be informed and enhanced by excellent research on learning and teaching science.

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