The Benchmarks for Science Literacy (AAAS 1993) and the National Science Education Standards (NRC 1996) strongly suggest that students should be engaged in hands-on learning. However, from many corners, the original “mental training” rationale for school labs has been criticized, the “cookbook” nature of laboratory exercises condemned, and the prevalence of using laboratories simply to verify previous classroom content questioned. These attacks are justified. Too frequently the school laboratory is far removed from the
recommendations of constructivist teaching and is at odds with the way scientists themselves investigate problems.

Abd-El-Khalick et al. (2004) illustrate that inquiry is again becoming a dominant theme in science curriculum policy discussions, both in the United States and throughout the world, with the laboratory suggested as the natural domain of inquiry instruction. The impact of inquiry teaching on learning is impressive. Smith (1996) and Mao and Chang (1998) in their meta-analyses of inquiry teaching conclude that inquiry methods of teaching science resulted in significantly improved mastery of science content, content retention, enhanced critical thinking skills, laboratory skills, and attitudes when compared with traditional teaching methods. Freedman (1997) has shown that ninth-grade physical science students with laboratory experiences demonstrated increased achievement and a more positive attitude toward science than those lacking such experiences. However, typical laboratory teaching will not result in the kind of inquiry recommended, so once again laboratory instruction is under the microscope. Just recently, the National Academies Press released the results of a major study titled America’s Lab Report: Investigations in High School Science (Singer, Hilton, and Schwiengruber 2005) [Editor’s note: See the Commentary on page 10.]

In order to enhance and revitalize laboratory teaching, one must recognize that not all laboratory activities have the same impact on learners. The cognitive component of the exercise is one of the most potent variables worth considering in predicting how a given activity will affect students and what learning it might foster.

Schwab (1962) first proposed and Herron (1971) later modified a taxonomy of laboratory activities based on an appraisal of how much information the students have as the activity begins (Figure 1, p. 27). In a Level 0 laboratory, the teacher provides both the problem and method of solution. In addition, the answer is known before the laboratory because of prior knowledge held by students gleaned from the textbook or classroom. Level 1 activities are better but do little more than give students the opportunity to follow a recipe in cookbook fashion and verify some preexisting facts. Students have no authentic opportunities to make decisions about the nature of the procedure or choice of the problem. Only in Levels 2 and 3 are students really acting as scientists in the choices they make about procedures and problems. Considering the level of the laboratory can help teachers make informed choices about the impact that a particular activity might have on student learning and motivation, and help move activities toward higher levels of inquiry.

Enhancing teaching and learning in the laboratory

In addition to understanding the level of the lab, a review of the research literature reveals a number of suggestions that will enhance the overall student laboratory experience. Consider the following:

**Encouraging long-term investigations**

Scientists rarely conduct investigations in which the solution is assured within an hour or so. In contrast, students typically work in the laboratory with the expectation that an answer will be achieved quickly by simply following directions. To counter this view, students should have opportunities to engage in long-term investigations and explore phenomena that simply cannot be observed in one or two class periods.

Several ways exist to encourage long-term activities even within the tight time constraints of the school day. First, longer exercises might take place out of school. Students could make daily or weekly observations of a living thing such as a tree or a pet hamster, the pattern of Moon phases, or the varying amount of daylight hours throughout the year. Allowing students to observe and discover patterns in nature is more effective than simply telling students that such patterns exist. Another strategy for long-term projects is to have students work on an extended activity for a few minutes each day. For instance, students could make observations of some phenomenon such as plant growth or crystal formation at the beginning of each class period. Alternately, students might work in groups on smaller parts of a longer project that they will later share with each other to visualize the whole process. This strategy could be extended through the internet to involve students working in other parts of the country on projects that might involve the analysis of groundwater pollution or on a census of an ecologically sensitive organism.

**Illustrating the authentic nature of science**

Accurate portrayal of the nature of the scientific endeavor stands at the core of all high-quality science teaching. Although the laboratory provides a unique opportunity for teachers to help students understand how scientists gain information, teachers must be cautious. Misconceptions regarding the nature of science can occur in the school science laboratory just by the teachers’ choice of language.

For instance, it is well known that scientists do not use a single standard step-by-step scientific method by which all phenomena are investigated (McComas 1998). However, by referring to the “scientific method” in class, students are likely to learn a significant misconception regarding the work of scientists. In addition, teachers frequently indicate that the results of a laboratory experience will prove scientific ideas in the way that proof is used in mathematics. Scientists do not prove ideas, but only fail to disprove them at that moment. Therefore, teachers should discuss the
role of the laboratory in providing evidence to help substantiate ideas. Another problem results when teachers refer to all work in the laboratory as experimental. Most scientists would label something an experiment only if it involves purposeful manipulations of nature with limited variables accompanied by an appropriate control for comparison. Few classroom laboratory activities are true experiments. It would be more reasonable to call such exercises “activities or observations” rather than give students the wrong idea about how science functions.

Finally, an additional philosophical issue presents itself when students fail to get the “correct” answer as expected by the teacher or textbook. When only one answer is expected or valued, students may come to believe that this is also the case in science. However, in science, results that deviate from what are expected are often among the most interesting and useful.

**Encouraging investigations at sites beyond the classroom**

The authors of *Project 2061* suggest that “science teachers should exploit the rich resources of the larger community . . .” in the design of lessons (AAAS 1989, p. 151). This implication supports an earlier call from Penick and Yager who state that students should see the world as their laboratory. The true investigative laboratory can be “in home, in nature, in [the students’] mind and any place students can investigate . . .” (1986, p. 7). Teachers and students alike should expand their definition and expectations of the laboratory experience and extend beyond the narrow confines of the traditional school laboratory. Scientists do not work exclusively in rooms called “laboratories,” yet for many students, the classroom laboratory setting must seem like the only possible research site. Broadening the investigative arena to include parks, nature centers, schoolyards, students’ home neighborhoods, botanical gardens, zoos, and museums will help students see that investigations can take place almost anywhere.

For example, teachers could refrain from telling students about the types of rocks in an area, but instead ask them to bring in an assortment of samples from the community for group identification or classification. Rather than asking students to memorize the parts of a flower, students could examine dozens of flowers at the local nursery. These flowers may appear unique but share many similar elements in their basic construction—as students may discover. Instead of having students read in their textbooks that there is variation within the species, a field trip to the zoo or a local pet store may establish this important fact.

**Using the laboratory to introduce concepts**

Most laboratory exercises offer no surprise to students. Typically, teachers discuss a phenomenon in a class presentation and then have students verify in the
laboratory what has been stated earlier in class. More inductive methods should be used so that the laboratory work precedes rather than follows the classroom discussion of a topic or principle. Requiring percent error calculations—typical in many chemistry and physics classes—is just another way of telling students that a “right” answer exists. Although such calculations can improve accuracy and critical thinking, such practices do not reflect the real purpose of investigations in science. The technique of performing laboratory work before extensive classroom discussions may be all that is necessary to raise the inquiry level of the laboratory.

The placement of the laboratory within the process of concept development is important. Ivins (1985) found that when laboratory work introduces rather than confirms a discussion of ideas, it is most effective in helping students learn. Raghubir (1979) discovered that students exhibit higher levels of cognitive ability when they actually gained knowledge through the laboratory rather than simply using the laboratory to verify what teachers and textbooks have stated. These findings support a constructivist view of learning that suggests students can only assimilate new information by generating personal understanding out of their own experiences. Making laboratory activities more valid educational experiences may be as simple as providing the hands-on experience before the lecture rather than with the order reversed as is frequently the case.

Giving students opportunities to make choices

Students rarely have much to say about the way in which an investigation is conducted despite the general acceptance of constructivism as an explanation of how learning occurs. Unfortunately, a report from the U.S. Department of Education (O’Sullivan and Weiss 1999) on student work and teacher practices found that 69% of U.S. 12th graders “never or hardly ever” designed and carried out their own scientific investigation.

In spite of the fact that generally students are not permitted to work independently and make personal decisions, the evidence is clear that when students are allowed a choice in the design and implementation of laboratory work, they perform better and enjoy the experience more. Eggelston (1973) and Leonard (1980) discovered that cookbooklike laboratories frequently bore students, but “the more involved a student is in the laboratory the more productive the educational outcomes will be” (Leonard 1980, p. 338). Students who were given more choices in the way they conducted investigations had higher scores on laboratory reports and quizzes and were able to work independently for longer periods than students not permitted such discretion (Cavana and Leonard 1985).

Assessing laboratory learning using authentic means

Laboratory work could be made more valuable as both an instructional and diagnostic tool through the use of authentic assessment. The term authentic assessment means that progress is measured in ways that match the instructional method or are related to some real-life task. Unfortunately, most laboratory assessment is accomplished with objective items, paper-and-pencil instruments (Hofstein and Lunetta 2004) rather than hands-on modes. Nonauthentic assessment plans simply do not reinforce the inquiry nature of exemplary laboratory teaching.

Many teachers require students to use a standard format when reporting the results of laboratory investigations. This standard format is easy for students to complete and straightforward for teachers to evaluate, but the practice encourages a degree of dishonesty when students report on a process that is far more creative than procedural. The typical lab report format can hide the true nature of the experimental discovery process, with all of its inherent false starts and dead ends. The pathway appears to be straightforward and the researcher’s steps unwavering, but this is rarely the case. To avoid this, students could be asked to write a narrative report describing their individual process of investigation rather than a forced convention disguising their personal method.

Authentic assessment could be enhanced with the use of practical laboratory and other variations of hands-on exams, but the inclusion of learning cycle–based activities would be even better. In the learning cycle, students first are encouraged to investigate on their own before moving onto the second stage during which the concepts are discussed more formally. In the final step of the cycle, students are asked to apply what they have learned. The application phase is an ideal place for authentic assessment.
Engaging students in cooperative or collaborative work

Cooperative learning has been widely touted as a useful pedagogical tool generally by researchers such as Slavin who states that such learning schemes encourage “students to discover, debate, diagram and ultimately to teach one another” (1991, p. 71). In a practical sense, group work is valuable because students will learn how to complete a team-based task by assuming various roles in ways that will prepare students as future employees (Cohen 1986; Schoenfeld 1989). When students work together, limitations on equipment and supplies as well as time constraints associated with laboratory tasks can be addressed effectively. Breaking down a large task into smaller parts as recommended in collaborative schemes gives students the opportunity to complete their assignments within the limitations imposed by time and materials. Philosophically, as well, group work in the laboratory is important so that students can simulate what scientists do as they solve problems and discuss what the results mean.

Using indirect verbal behaviors when responding to students

Although the instructor orchestrates the laboratory experience, some teacher actions are more effective than others in supporting a high-quality laboratory experience. Facilitation, not just interruption, is one such supportive laboratory teacher behavior. Students are distracted and even annoyed when teachers stop their work repeatedly during the class period to add a forgotten direction, explanation, or procedural note. Once students are working, the best interaction technique is to guide in such a way that students know their individual work is valued but that the teacher is ultimately in control.

Collins and Stevens (1983) and others have described a true inquiry approach to instruction as an alternative to more didactic methods. Inherent in inquiry instruction in the laboratory is the strategy that the discourse between teacher and students should be an authentic conversation rather than one based on an authoritarian structure in which students see the teacher as the ultimate source of approval and information. An indirect style of response to inquiries causes students to look within themselves or within the group for guidance. Indirect questions such as “I wonder what makes you think that?”, “Have you considered . . .?”, or “How would you find out?” are more thought provoking than simply answering the question.

Engaging and interacting briefly with small groups of students

Highly-skilled teachers move from one group of students to another, monitoring, encouraging, and questioning, but generally avoiding long periods of contact with any single student group (McComas 1991). If the teacher is available but not intrusive, students will appreciate the support and react in a positive way to the teacher’s interest.

This technique is also valuable to the teacher in evaluating student interest and concerns. Should one group of students discover something interesting or demonstrate a common problem, the instructor is in an excellent position to react appropriately and constructively. Rather than stopping the entire group of students to share a concern with the technique or an interpretation of the results—a typical response on the part of the teacher—the instructor can easily spread the word with each group visited. Because this technique is based on frequent but brief teacher visits with each student group, the message quickly is spread throughout the classroom. This management mode can also be used as part of the assessment strategy. The instructor can use a formal checklist to ascertain how well each student is completing a technique or process or can make general notes about the degree to which students are engaging in the laboratory.

Putting it all together

Teachers can enhance laboratory teaching by trying one or more of these suggestions and gauging the impact on student learning and attitudes or can blend several of these ideas together through the “challenge-lab approach.”

Challenge labs begin when a thought-provoking question is provided to students in the briefest fashion possible. Leonard (1991) suggests that teachers should give students a task or goal providing only essential procedures, while refraining from telling students how to complete the investigation; students could work cooperatively using a list of resources from which they may choose to guide their investigation thus forcing students to think for themselves. This technique may be used in all educational settings as long as the students and teacher are prepared for the experience. Students must know what is expected of them and understand what the teacher is equipped to provide them. The teacher must avoid being too helpful in assisting students with problem solving since this can defeat the effectiveness of this innovation.

Such a plan will require that laboratory instructors spend minimal time on explanations and directions given before laboratory work. Teachers should deal mainly with procedural and safety issues or in the demonstration of apparatus while avoiding any focus on the expected results of the activity. In the best challenge labs, the emphasis will instead be placed on the postlab debriefing, which will establish the link between the laboratory and lecture components of the lesson. Here students will pool their data and discuss conclusions supported by the data. Frequently, students themselves establish the underlying generalization governing the phenomenon observed with
minimal help from the teacher. This approach is difficult to implement with students who are accustomed to step-by-step exercises. In time and with practice, students will come to expect and enjoy the challenge-lab approach as they gain the necessary skills and confidence to conduct inquiries on their own.

The debate about the role and nature of laboratory teaching has been both fruitful and frustrating. It is frustrating if one simply compares some version of “laboratory teaching” to “nonlaboratory teaching” in terms of content acquisition and finds that little justification exists for continuing the tradition of laboratory instruction. The problem is that most laboratory activities are not well conceived or executed and, in reality, add little to teaching and learning in school science. Only when we recognize that not all laboratory experiences and teaching plans are the same can we make the most useful judgments about the value of high quality hands-on instruction. The research focused on true inquiry is quite clear—it is effective in a variety of ways. The best laboratory experiences are stimulating and enjoyable and enhance content learning and the development of positive attitudes toward science. The rewards are great, but so too are the challenges. It takes time to develop the kinds of laboratories that will serve students most effectively. It requires experience on the part of teachers to engage students in supportive ways without interfering and it takes practice on the part of students to grow accustomed to the responsibilities and opportunities that occur when verification-based, cookbook laboratories are replaced by authentic inquiry learning experiences. However, the result is worth the effort.

William F. McComas is director of the Program to Advance Science Education at the University of Southern California, Rossier School of Education, WPH 1001e, Los Angeles, CA 90089; e-mail: mccomas@usc.edu.

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