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Using the Laboratory to Enhance Student Learning

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> *There are important differences between tasks and projects that encourage hands-on doing and those that encourage doing with understanding....*
> (Bransford, Brown, and Cocking 2000, 24).

In *Alice in Wonderland*, Alice asks which way she should go, and is told, "That depends a good deal on where you want to get to." Similarly, before addressing the role of laboratory experiences, where we wish to take students must first be articulated. For instance, developing deep, robust, and long-term understanding of science concepts is one aim of the *National Science Education Standards* (NRC 1996), but the vision also includes an understanding of the nature of science and the attributes and skills that make for effective science inquiry. NSTA's popular *Focus on Excellence* monograph series (Bonnstetter, Penick, and Yager 1983; Penick 1983a, 1983b; Penick and Bonnstetter 1983; Penick and Lunetta 1984; Penick and Meinhard-Pellens 1984) suggested that the goals listed below were commonly associated with exemplary science teaching:

- Convey self-confidence and a positive self-image.
- Use critical thinking skills.
- Convey an understanding of the nature(s) of science.
- Identify and solve problems effectively.
- Use communication and cooperative skills effectively.
- Actively participate in working toward solutions to local, national, and global problems.

- ◆ Be creative and curious.
- ◆ Set goals, make decisions, and self-evaluate.
- ◆ Convey a positive attitude about science.
- ◆ Access, retrieve, and use the existing body of scientific knowledge in the process of investigating phenomena.
- ◆ Demonstrate deep understanding of science concepts.
- ◆ Demonstrate an awareness of the importance of science in many careers.

The task is formidable and reaching these lofty goals will not occur without rethinking laboratory activities and the role of the teacher so they reflect how people learn and promote student actions consistent with the desired state set forth in the *National Science Education Standards* (NRC 1996) and *NSTA Pathways to the Science Standards, High School Edition* (Texley and Wild 1996).

How People Learn

Science teachers are well aware that even when they explain ideas slowly, carefully, and clearly, students often fail to grasp the intended meaning. Understanding how students learn—and why they often struggle to grasp our intended meaning—is the foundation of informed teaching. To achieve robust long-term understanding, multiple connections must be erected and grounded in experience, but unfortunately these links cannot simply be given to students. Fundamental to our understanding of learning is that students must be mentally active—selectively taking in and attending to information, and connecting and comparing it to prior knowledge in an attempt to make sense of what is being received. However, in attempting to make sense of instruction, students often interpret and sometimes modify incoming stimuli so that it fits (i.e., connects) to what they already believe. Consequently, students' prior knowledge that is at odds with intended learning can be incredibly resistant to change. Driver (1997) argued that

> *some of the more complicated learning we have to do in life, and a lot of science is like this, involves not adding new information to what we already know, but changing the way we think about the information we already have. It means developing new ways of seeing things.*

Toward this end, effective laboratory experiences are highly interactive and make explicit students' relevant prior knowledge, engender active mental struggling with that prior knowledge and new experiences, and encourage metacognition. Without this, students will rarely create meaning similar to that of the scientific community. That is why typical cookbook laboratory activities do not promote, and often hinder, deep conceptual understanding; they do an extremely poor job of making apparent and playing off students' prior ideas, engendering deep reflection, and promoting understanding of complex content. Such activities mask students' underlying beliefs and make desired learning outcomes difficult to achieve.

Hands-On Is Not Enough

For decades, hands-on experiences have been promoted as the solution to helping students learn science. That direct experience will improve students' understanding seems intuitively obvious, but evidence indicates that such experiences, by themselves, do not lead to a scientific understanding of the natural world. In *Minds of Our Own* (1997) college graduates, despite their everyday hands-on experience with mirrors, incorrectly state that if they move closer to or further away from a mirror in which they can see only half their body, then they will be able to see their entire reflection. A barber who spends his days in front of a mirror conveys the same misconception, illustrating that experience alone is insufficient for developing a scientific point of view. Such experiences, like cookbook laboratory activities, do not force us to confront a different way of looking at the mirror. Hands-on experiences, by themselves, are insufficient for coming to an understanding of the scientific community's explanation for natural phenomena—students must also be mentally engaged. Pre-fabricated cookbook activities, so ubiquitous in science teaching, rarely engage students in ways necessary to facilitate such an understanding. As Bransford, Brown, and Cocking (2000) write, "Hands-on experiments *can* be a powerful way to ground emergent knowledge, but they do not alone evoke the underlying conceptual understandings that aid generalization" (22).

To understand why traditional hands-on experiences fail to meaningfully engage students, consider the following questions that must be asked in authentic scientific inquiry:

- What is known and what questions are raised by this knowledge?
- What investigative procedure will address particular questions?
- What equipment is necessary to carry out this procedure?
- What data is relevant and should be collected?
- How will the data be analyzed?
- What does the data mean?
- What mathematical calculations, if any, are required and in which order should they occur?
- How is the work to be communicated to readers?

In typical cookbook laboratory experiences, most all these decisions are made *for* students. Not only does this misportray the nature of scientific inquiry, but because most all the thinking is done for students they have little reason to engage in the cognitive activities known to be essential for robust learning (e.g. selectively considering and attending to information and comparing it to prior knowledge). Moreover, teachers get a poor picture of what students know and can do, which hinders dialogue and lesson planning that would deliberately move students to that desired learning. Using the laboratory to enhance student learning requires a reconceptualization of science activities.

Restructuring Science Activities

Saunders (1992) noted that

> *[c]ognitive activities such as thinking out loud, developing alternative explanations, interpreting data, participating in cognitive conflict (constructive argumentation about phenomena under study), development of alternative hypotheses, the design of further experiments to test alternative hypotheses, and the selection of plausible hypotheses from among competing explanations are all examples of learner activities which [mentally engage students].* (140)

However, science teachers are far too busy to invent every laboratory experience from scratch so that they are more consistent with how students learn and so that they reflect desired goals for students, the *National Science Education Standards*, and the nature of science. As Clark, Clough, and Berg (2000) state,

> *In rethinking laboratory activities, too often a false dichotomy is presented to teachers that students must either passively follow a cookbook laboratory procedure or, at the other extreme, investigate a question of their own choosing. These extremes miss the large and fertile middle ground that is typically more pedagogically sound than either end of the continuum.* (40)

They suggested that effective laboratory experiences can be created by modifying existing activities so they make explicit students' relevant prior knowledge, engender active mental struggling with that prior knowledge and new experiences, and encourage metacognition. To illustrate this, they presented in some detail how the common cookbook laboratory activity addressing the mass percent of water in a hydrate was altered so that students engaged in the cognitive activities essential for active learning. In an earlier article, Clough and Clark (1994a) presented a cookbook laboratory activity they had picked up at an NSTA national convention and showed how they modified it to ascertain their students' prior knowledge, require metacognition, and confront a common chemistry misconception.

When modifying traditional laboratory activities into experiences that are far more likely to promote learning and other important goals we have for students, teachers should:

1. Require students to make explicit their prior knowledge.
2. Structure and scaffold activities so that students must access and employ previously studied science ideas—that is, ensure that activities reflect a spiraling curriculum.
3. Determine whether the experience is to be primarily an exploratory or application activity.
4. Where appropriate, include students in setting the lab question to be investigated.
5. Where appropriate, have students invent laboratory procedures (consider safety, equipment, and cognitive issues).
6. When students cannot invent laboratory procedures, structure the experience so students *must* be mentally engaged in the lab.
7. Use materials and equipment that are no more complex than necessary.
8. Force students to consider and defend what data are relevant and irrelevant.
9. Have students decide what their data means.
10. Require students to apply mathematical reasoning to problems.
11. Make students responsible for communicating their lab work in a clear manner.
12. Have students set goals, make decisions, and assess progress.
13. Ask questions that spark ideas and reduce student frustration.
14. Refrain from summative evaluations of students' ideas and interpretations.

Most of these suggestions are illustrated in articles appearing in *The Science Teacher* (Clough and Clark 1994a, 1994b; Colburn and Clough 1997; Clark, Clough, and Berg 2000), but three require further discussion here. For instance, how does exchanging complex laboratory equipment with more simple everyday materials promote learning? When equipment (even when it is not particularly complex) is used before students have seriously grappled with the concepts under study, they often incorrectly assume that the equipment is an essential part of the concept. For instance, after students used a bulb holder in a batteries and bulb activity to illustrate circuits, interviewers (*Minds of Our Own* 1997) found that one of the brightest students in the honors physics class thought the bulb holder was a necessary part of a circuit. The presence of this rudimentary piece of equipment and its "black box" nature not only clouded the purpose of the bulb holder but also created a misconception regarding the basic concept of a circuit, upon which many other science concepts are built. In redesigning laboratory experiences, care must be taken to avoid using equipment too far removed from students' conceptual understanding. As with science concepts, teachers need to scaffold the use of science equipment so that students grasp what the equipment is doing for them and do not mistakenly couple the equipment to the concept.

Another consideration in modifying activities is deciding whether the redesigned experience is to serve primarily as an exploratory or application activity. If activities are appropriately scaffolded, then explorations will require students to apply previously addressed concepts even though the chief purpose of the modified activity is to ensure that students have relevant and concrete experiences prior to discussing science concepts illustrated in the activity. In these cases, laboratory modifications emphasize having direct experience precede verbal instruction so that students will bring to the surface their prior knowledge, raise questions, and connect future verbal abstractions to the concrete experiences. When modifying laboratory activities to serve as applications, changes should be made with the primary purpose of having students use what they have learned in unique situations.

What to do when students, for either safety or cognitive reasons, must follow a step-by-step procedure appears to be a vexing problem in promoting more effective laboratory experiences. The solution is to structure these experiences so students *must* be mentally engaged while following the given procedure. A number of ways exist to do this, but an easy change is simply to pose questions at each step of a procedure that forces students to consider the rationale for the step. Below are just a few examples of questions I inserted (italicized) in a traditional step-by-step procedure my students followed to determine the heat of combustion of a candle.

1. Determine and record the mass of an empty 12 oz soda can. *What is the importance of determining the mass of the can? What about a 12 oz soda can makes it particularly suited for this experiment?*
2. Add 90–100 mL of water to the soda can. Drop small pieces of ice into the soda can a few at a time until the temperature of the water is lowered to 9º to 10ºC below room temperature. Be very careful not to allow the temperature to fall any lower than this. Remove any unmelted ice. *What is the significance of 90–100 mL? What is the rationale for lowering the water temperature 9º to 10ºC below room temperature? How would the results be different if you lowered the temperature a different amount?*
3. Weigh the can plus the water. Record this mass. *What is the importance of weighing the can again?*
4. Place the candle under the can of water and light the candle. Stir the water gently with a stirring rod as it heats. *How would not stirring the water affect your results? What error is being introduced by stirring the water with a stirring rod? Why stir the water gently rather than briskly?*
5. Continue heating until the temperature rises as far above room temperature as it was below room temperature at the start of the experiment. *What is the rationale for heating the water as far above room temperature as it was below room temperature at the start of the experiment? What would happen if you didn't?*

Such questions are not trivial because they force students to engage mentally in understanding the laboratory design and science concept being investigated. For instance, my students were bewildered at my question regarding the 12 oz soda can, seeing it as simply a container for water. After I asked additional questions, they made the connection that the thin aluminum wall of the can was important in maintaining, within reason, that heat lost by the candle is gained by the water—a critical conceptual claim in the experiment. Understandably, the approaches suggested above are initially frustrating to students accustomed to thoughtlessly following directions, and consequently, the role of the teacher is pivotal for engaging students in a manner reflecting how we know people learn.

The Critical Role of the Teacher

Such modifications make the teacher's role in student learning far more critical, for without well-reasoned teacher intervention in both the designed lab structure and its implementation, students will become frustrated because alone, they will rarely create meaning similar to that of the scientific community. Science ideas appear obvious once a deep and accurate understanding exists, but for students in the midst of piecing together such understanding, it is not at all obvious! Without a teacher's perceptive questioning and responding that plays off students' observations, actions, and thinking, they would rarely put together intended ideas in an accurate fashion. This intervention is considerably different than that occurring in most science classrooms today (Penick 1991) and reflects a different perspective on how people learn. Sympathizing with the difficult task of understanding how people learn and the need to change the teacher's role, Driver (1997) stated that

> *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.*

However, the already overwhelming demands placed on teachers make difficult the learning and introduction of new teaching strategies. Fortunately, the gentle approach to changing laboratory activities also applies to changing the teacher's role in those activities. By gradually shifting to the new strategies and teaching behaviors listed below, as advocated by Colburn and Clough (1997), teachers and students can become accustomed to new roles with less stress.

1. Conduct an exploratory lab experience prior to verbally introducing content.
    - Increases interest
    - Reflects how we tend to learn
2. Discuss the lab before verbally introducing content.
    - Increases interest in the interactive information presentation that follows
    - Reflects how we tend to learn
3. Require students to decide how lab findings will be communicated.
    - Requires students to think and be creative
    - Reduces boredom of reviewing students' lab reports
4. Change the test.
    - Assessment should reflect the course goals
    - Students place importance on what is being assessed
5. Begin changing your role during the activity.
    - Essential core of effective teaching (Effective questioning, wait-time, encouraging nonverbal behaviors, listening, and nonevaluative responding)
    - This is the most difficult step as patterns are difficult to change
6. Have students invent the procedures to answer a lab question.
    - The teacher's role is critical (high expectations require high support)
    - Most of the decisions about how to answer a question must be on the students' shoulders, but the teacher's role is critical in supporting students
7. Continue changing your role during the lab activity.
    - Keep working to implement the essential core
    - Audiotaping and videotaping are crucial for advancing practice
8. Employ application lab experiences so students must use what they learn in new contexts.
    - Inquiry now reflects what students have learned
    - Inability to apply often indicates lack of understanding
    - Some application activities also serve as exploratory activities for further learning

9. Have students invent lab questions and procedures.
    - May only occur once or twice in a school year and makes for an excellent year-end final exam
    - May simply be hypothetical

Modifying the structure of preexisting cookbook labs, asking effective questions, incorporating appropriate wait-time, carefully listening, acknowledging and playing off student ideas, and exhibiting positive nonverbal behavior (e.g., smiling, maintaining eye contact, leaning forward when students are speaking, raising eyebrows to show interest) are all key for creating the mentally engaging and productive environment conducive to learning.

The end result appears to a layperson as simply hands-on learning, but to the expert teacher who is sensitive to the intricacies of learning, it is far more complex than that. Both the student and teacher are thinking, but on different planes. The most significant difference is that while *students* are connecting these hands-on experiences to their current and emerging conceptual framework, the *teacher* is desperately trying to understand students' thinking to further engage them in that construction of knowledge. Hence, placing greater responsibility on students does not mean simply having them figure things out on their own. Rather than abdicating responsibility for teaching, an understanding of how people learn demands from teachers a far more complex and demanding role in promoting students' understanding of science.

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