Science and Engineering

Two models of laboratory investigation

Jennifer Harkema, James Jadrich, and Crystal Bruxvoort

The following scenarios describe lab activities commonly performed in high school science classes:

- *Scenario A:* Students studying gravity determine the value of the gravitational constant *(g)* by dropping balls from various heights and timing how long it takes them to hit the ground. Lab grades are based on how closely results compare to the expected value (9.8 m/s^2).
- *Scenario B:* Students build a model rocket fueled by water and effervescent tablets. Points are awarded based on the height reached by the rocket. Extra credit is awarded to the student whose rocket reaches the highest height.
- *Scenario C:* Students design an experiment showing that light intensity affects the rate of photosynthesis in *Elodea*.
- *Scenario D:* Students determine the density of various objects.

Laboratory activities have an important place in the science classroom. They introduce students to science concepts and at the same time, teach them about scientific processes and the nature of science (McComas 2005). While the value of these activities is clear, teachers should be wary of incorporating too many lab activities like those described above. Although lab experiences like these are beneficial to students, they have the capacity to reinforce a false notion of scientific experimentation—namely that its purpose is to achieve a prescribed outcome. In this article, we focus on this misconception and offer suggestions for how teachers can

Addressing the Standards.
The National Science Education Standards (NRC 1996) addressed in this activity include:

- Science as a human endeavor (p. 170)
- Nature of scientific knowledge (pp. 170–171)

better portray the true nature of scientific experimentation to students.

Types of experimentation: Science versus engineering

Understanding the nature of scientific experimentation is important in today's science classroom (AAAS 1990; AAAS 1993; NRC 1996). Scientific literacy—the goal of science education—requires not only a broad understanding of content, but also of the methods, purposes, and even limitations of scientific investigations.

As science teachers, we know that students often have preconceptions that are inconsistent with accepted scientific views and complicate science learning (Driver, Guesne, and Tiberghien 2002; Gomez-Zwiep 2008). Less well-known is that students' preconceptions also influence the way in which they perceive laboratory activities. As a result, some develop a false notion about the nature of scientific experimentation.

Scientific experimentation, rightly understood, is the examination of cause-and-effect relationships, with the goal of finding and understanding causal mechanisms in nature. This type of experimentation is referred to as the "science model" (Schauble, Klopfer, and Raghavan 1991). These types of experiments ask questions such as: What affects reaction rates? and Is free-fall acceleration independent of mass? Figure 1 presents an activity that transforms Scenario A (p. 27) into a science model investigation.

A second experimental approach is characterized by the manipulation of variables to produce a desired outcome. This type of experimentation is referred to as the "engineering model" (Schauble, Klopfer, and Raghavan 1991) and reflects, to a large degree, the inherent concern of engineers. Scenario B (p. 27), in which students are asked to build a rocket that launches as high as possible, is one example.

Of course, practicing scientists and engineers often employ both the science model and the engineering model when conducting research. Dewey (1913) suggests that both approaches to experimentation are important—one in a practical sense for the purpose of achieving a desired effect (engineering model), and the other for the purpose of achieving scientific understanding (science model). Both models have an important place in the science classroom.

However, research has shown that students do not easily distinguish between the science model and the engineering model of experimentation (Kuhn and Phelps 1982; Schauble 1990; Schauble et al. 1991; Tschirgi 1980). Popular media portrayals of scientists and engineers at work can even unintentionally lead students to conflate these two models of experimentation (Figure 2).

In most classroom labs, students are often predisposed to employ only the engineering model—when they should be using the scientific model (Schauble et al. 1991). For example, Schauble et al. (1991) report that students asked to investigate the effects of a car's design on speed became wrongly preoccupied with constructing fast cars (i.e., the engineering model). In this activity, the intention was for students to use the science model to investigate the effect of car design on speed; instead, they interpreted the purpose of the activity

FIGURE 1

Science model example.

The following lesson was inspired by Scenario A (p. 27) at the beginning of this article. Instead of calculating the acceleration due to gravity, students determine what variables affect how fast an object falls. The teacher introduces this activity with a demonstration in which he or she drops a weighted film canister and a folder from about shoulder height. Students observe the film canister fall at a faster rate. After some discussion, they are presented two competing hypotheses:

1. Size (and shape) determine how fast an object falls.
2. Weight determines how fast an object falls.

Student groups are asked to test which, if either, of these hypotheses is correct. They must do this by designing fair tests (i.e., control variables) using film canisters, small washers, masking tape, and manila folders.

Some students may try to determine if weight matters by using two film canisters of the same size that contain different amounts of weight. These students conclude that weight does not affect acceleration, as both canisters hit the ground at the same time. Other students will test the effect of weight by using identical folders, made unequal in weight by taping washers to one folder. In this case, they conclude that weight does have an effect. Some students may test for size and shape by simultaneously dropping a crumpled folder and a flat folder, leading to the conclusion that size and shape matter.

A large group discussion brings out the full complexity of the situation. Students cannot simply state that weight or size alone determines how fast an object falls because both variables, in certain cases, have an effect on the result. However, students can use their testing (along with the teacher's guidance) to conclude correctly that when objects are small in size—compared to their mass—weight does not matter. The lesson should not conclude without discussing important aspects of the scientific process, including fair testing, the tentative nature of scientific knowledge, and the use of disconfirming evidence to substantiate conclusions.

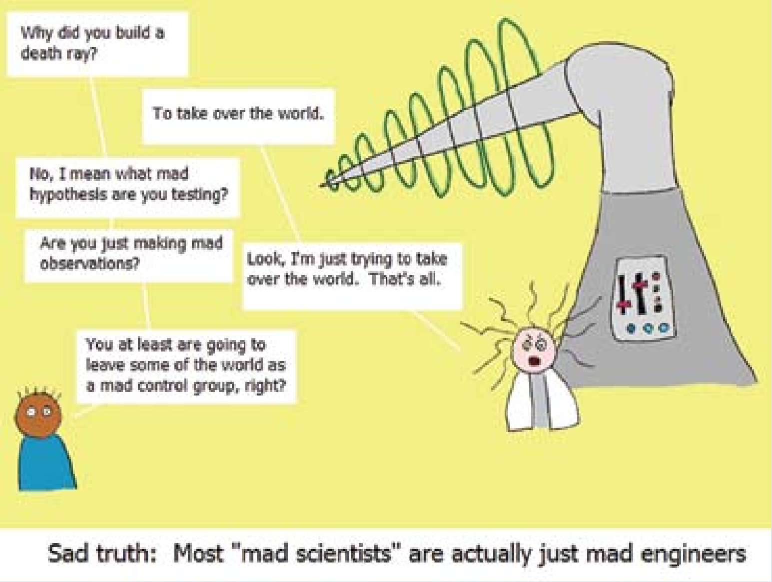
as optimizing a desired outcome—that is, designing fast cars.

Consequently, when teachers assign numerous lab activities that anticipate a prescribed outcome (e.g., show that $g = 9.8\ m/s^2$ or demonstrate that light intensity affects photosynthesis), they reinforce the misconception that scientific experimentation is mainly about achieving a specific outcome—and not about finding relationships among variables. The challenge of achieving a specific outcome encourages students to use a sort of trial-and-error approach in the laboratory. Instead of thoughtfully applying concepts and designing experiments to explore cause-and-effect relationships, many students work toward attaining the prescribed result—and bypass the opportunity to develop important conceptual understanding.

FIGURE 2

Death ray (Kulkarni 2009).

Popular media's portrayal of scientists and engineers at work can unintentionally reinforce misconceptions of both the science and engineering models of experimentation.



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Implications for science teachers

Students should understand and be proficient in using both the science and the engineering models of experimentation. Since students often are predisposed to using the engineering model, teachers must intentionally design activities that better reflect the nature of scientific experimentation. We recommend considering the following guidelines when creating and implementing science labs:

- *Caution against using verification labs:* Labs in which students are asked to confirm an expected outcome portray science in ways that are at odds with how scientists investigate problems (McComas 2005; Lunetta, Hofstein, and Clough 2007). These types of activities encourage the misconception that the engineering model is the only model of experimentation. Therefore, the use of verification labs should be carefully balanced with the use of labs that employ the science model.
- *Explore and apply:* Instructional design should involve labs in which students first explore a concept by studying the relationships between causes and effects (Marek, Maier, and McCann 2008). Once students have developed an understanding of how important variables affect an experimental situation, they can be challenged to use the engineering model and apply their newly formed conceptual understanding to generate a product or maximize an output. In this manner, the science model is employed early on in the exploration phase of the lesson, and the engineering model is used in a subsequent phase of the lesson as an application of student understanding.

  For example, consider Scenario B, in which students design rockets. This activity could be revised so that students first determine whether the amount of water, number of effervescent tablets, or fin size affects rocket height. This encourages students to focus on controlling variables to determine whether or not rocket height depends on any of these three variables. After students have distinguished the important variables, they can apply their knowledge by designing a rocket that will travel to the highest height.
- *Careful design of research questions:* Word choice can influence students' perceptions of the nature of science (McComas 2005). As an example, consider Scenario C (p. 27), in which biology students are challenged to show that light intensity affects the rate of photosynthesis. The wording of this question encourages students to use the engineering model. A slight rephrasing of the research question from "Design an experiment to show that light intensity affects the rate of photosynthesis in *Elodea*" to "What effect (if any) does light intensity have on the rate of photosynthesis in *Elodea?*" explicitly invites students to explore the possible effect of a variable.
- *Careful use of competition in the classroom:* Competitions, such as those described in Scenario B, can motivate students to really engage in science class (Fennema

and Peterson 1987). However, activities involving competition in the classroom typically reinforce the engineering model. Such challenges should not be overused, but rather balanced carefully with activities using the science model.

- *Test competing hypotheses:* Students are taught to look for supporting evidence to justify their ideas (Nickerson 1998). However, if students are asked solely to present or find evidence *for* an idea, but are very rarely asked to construct evidence *against* an idea, they are led to believe that science is only concerned with confirmation—a form of the engineering model.

If students are asked to determine the value for the gravitational constant *(g),* (e.g., Scenario A, p. 27) or show that light intensity affects the rate of photosynthesis (e.g., Scenario C, p. 27), their task is mainly to seek confirming evidence. In science, however, theory making involves seeking confirming *and* disconfirming evidence. A balanced laboratory curriculum tasks students with testing competing hypotheses and generating evidence both for and against proposed scientific ideas.

For example, instead of asking students to calculate the acceleration due to gravity (Scenario A), students can be challenged to test the determining factor that affects how fast an object falls: the object's weight or its size and shape (Figure 1, p. 28). Similarly, instead of asking students to determine the density of various objects (Scenario D, p. 27), students can be challenged to test whether weight alone, size alone, or shape alone determines its density. Instead of doing straightforward exercises seeking confirmation of known results, students are challenged to engage in nontrivial exercises that better reflect the true nature and process of science.

Conclusion

Teachers want to teach correct scientific understanding and incorporate lab activities effectively and efficiently. As a result, they may feel compelled to overuse lab activities that favor the engineering model of experimentation. However, "accurate portrayal of the nature of the scientific endeavor stands at the core of all high-quality science teaching" (McComas 2005, p. 25). Our goal as teachers is to design labs that reflect the nature of scientific experimentation and teach fundamental concepts, while simultaneously challenging students to use and understand both the scientific and engineering models of experimentation. ■

Jennifer Harkema (jen.harkema@gmail.com) *is a science teacher at Unity Christian High School in Hudsonville, Michigan; James Jadrich* (jjadrich@calvin.edu) *is a professor and Crystal Bruxvoort* (cb29@calvin.edu) *is an assistant professor, both at Calvin College in Grand Rapids, Michigan.*

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