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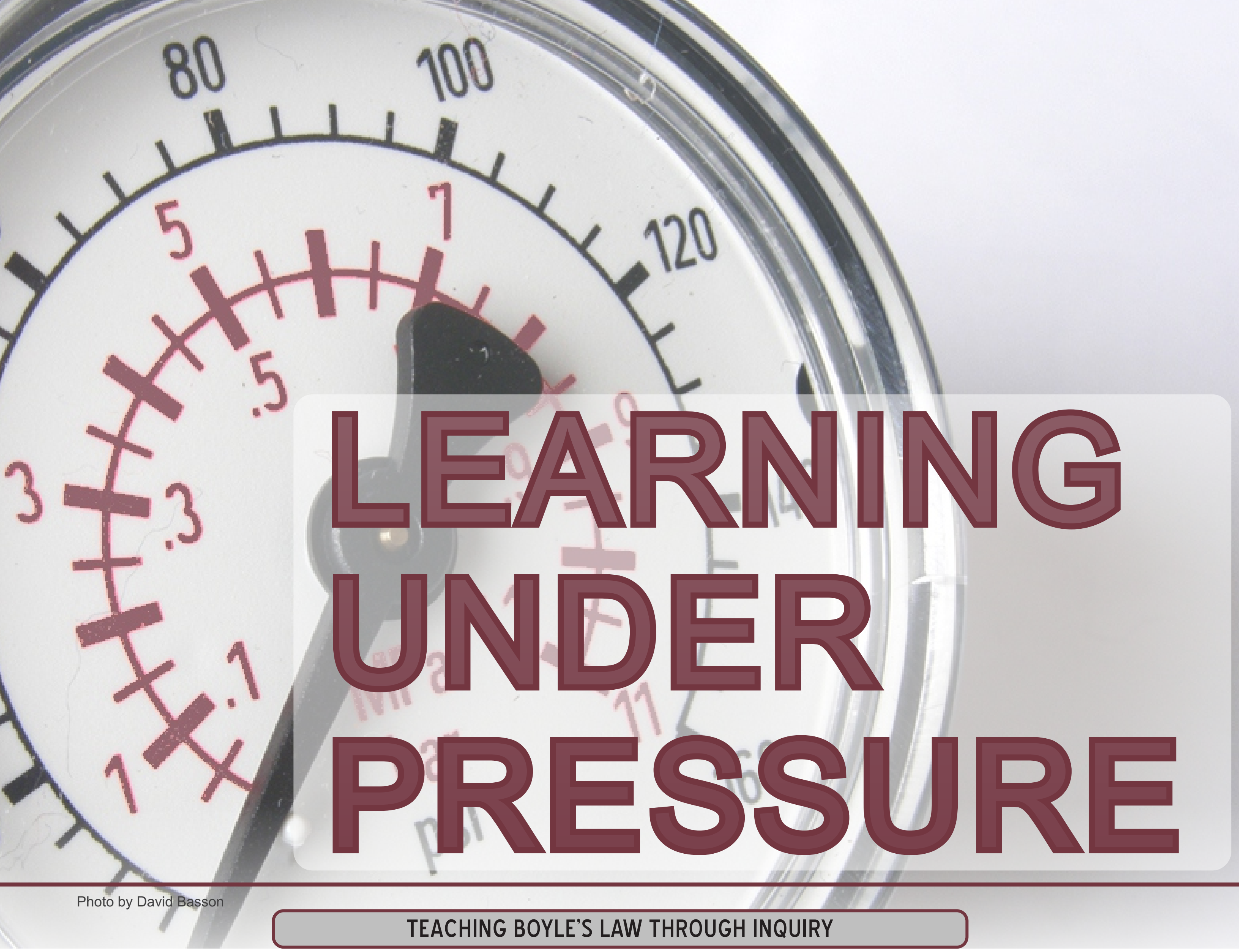

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LEARNING UNDER PRESSURE

TEACHING BOYLE'S LAW THROUGH INQUIRY

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ABSTRACT: Boyle's law is commonly addressed in chemistry and physical science textbooks, but rarely in a manner consistent with what we know best promotes learning (Bransford, Brown & Cocking, 2000). We present the standard syringe activity as an exploratory inquiry experience followed by a more formal development of the relationship. The activity starts and concludes by having students examine how the volume of a crushed pop bottle changes in a vacuum. Through iterative concrete experiences and guided discussions, students construct Boyle's law to account for the class data. This article address National Science Education Standards A, B, E, G, and Iowa Teaching Standards 1, 2, 3, and 5.

Most secondary school physical science and chemistry curriculum materials provide activities and explanations regarding the gas laws. Oftentimes the activities provided are cookbook experiences that come after the particular gas law has already been presented. Students simply follow step-by-step directions designed to illustrate or verify the gas law. This sequence of instruction does not promote the mental engagement necessary for learning, and it places abstract generalizations (i.e. the mathematical expression of a relationship) before experience. By placing concrete experiences prior to and alongside content development, and by using an inquiry-based approach, students are better able to understand science content (Karplus, 1977; Colburn & Clough, 1997).

Beginning the Activity

We begin this activity with a simple demonstration using a plastic 20-ounce soda bottle and a vacuum chamber. This simple demonstration provides students with an often-surprising experience to ignite interest in the lesson. Throughout the demonstration, we pose open-ended and thought-provoking questions to determine students' thinking and maintain interest. In addition to questions, we have to be highly engaged in the demonstration through excited body language and facial expressions(Clough, 2007). We start by having students squeeze a capped plastic soda bottle, and have them report how much they are able to depress the sides of the container. We ask students to provide an explanation for what is causing the resistance felt. Most students will accurately note that the air in the bottle causes the resistance. We then open the bottle, crumple the sides, replace the cap, and ask the following questions:

- "What happened to some of the air in the bottle when I squeezed it?"
- "How much volume does this container currently hold compared to what it once did?"
- "How much air is in the crumpled bottle compared to the original bottle?"

These thought-provoking questions, and those that follow throughout the activity require the use of appropriate wait-time I (at least 3-4 seconds after having asked a question) and wait-time II (waiting after a student responds) (Rowe, 1986) and encouraging non-verbal behaviors to promote student responses and further discourse.

We then place the crumpled, sealed bottle inside of a vacuum chamber and ask students to predict what will happen to the bottle once a vacuum is applied. Depending on our students' previous experience working with a vacuum, we may need to explain that a vacuum pump reduces the pressure surrounding the crumpled plastic bottle by removing air from inside the bell jar. Students are often surprised when the bottle uncrumples even though the lid remains tightly sealed on the bottle. We draw the students' attention to the consistent amount of air in the bottle. To accomplish this, we ask the students three complimentary questions.

- "Given that the lid is tightly sealed on the bottle, what can we conclude about the amount of air in the bottle?"

[Students usually acknowledge that the amount of air remains the same, but be prepared to ask further questions if students seem hesitant or provide an incorrect response.]

- "What changed in this system when we turned the vacuum pump on?"
- "How then do we account for the crumpled bottle expanding?"

To finish this beginning demonstration, we turn off the vacuum pump and permit air to rush back into the bell jar (equalizing the pressure in the bell jar and the room) and remove the bottle from the vacuum. Students are again amazed when the bottle collapses back to its previous volume. We inform the students that they will explore why this happens by determining how pressure and volume are related. We then proceed to ask students to share their initial thinking that would explain what they have observed. This raises our essential question: how are pressure and volume related?

Student Inquiry

We show students a capped 50 cc syringe (Figure 1) and ask them to draw parallels between the syringe and the soda bottle. Students typically identify that the air in both the pop bottle and the syringe is trapped and cannot escape. After we discuss the similarities, we ask students about the advantages of using a syringe with accurately labeled volumes instead of a soda bottle. Students easily note that

FIGURE 1
Boyle's Law syringe with wooden base and top.

Photo courtesy of www.homesciencetools.com

being able to know the volume of the air inside the syringe may provide useful data for our investigation.

We always model proper use of the capped syringe to alleviate many potential safety issues. However, we cannot rely on modeling alone, thus we draw explicit attention to how the syringes should be handled. For instance, we have students predict what will happen if, when the syringe cap is in place, the plunger is pushed down without the syringe being securely in the wooden base. Students will respond with a variety of ideas including 'the cap will fly off', 'the plunger will go down', and 'you won't be able to push the plunger down'. We draw students' attention to the dangers of flying syringe caps, and make clear that no pressure should be placed on the syringe plunger until the pointed end of the syringe is securely placed in the wooden base.

Qualitative Investigation

After some initial demonstration of the syringes, we then have students, in groups of two, develop a procedure to test how differing pressure on the plunger will impact the volume in the syringe. We typically provide no more than five to ten minutes for each group to develop their procedure and convey it on large white boards we have provided. Having students convey their ideas on white boards provides us with a way to assess their thinking and better monitor on-task behavior.

This first experience with the syringes does not need to be highly controlled. We want students to gain experience working with the syringes and explore how volume and

pressure are related. The class will develop a more detailed and quantitative approach after this initial exploration.
While students are crafting their procedure, we walk around observing what they write and listen to what they say. Our interaction is primarily directed at requesting clarification of their procedure. For instance, we often ask

- "How will you specifically alter the pressure/force on the plunger so that you can compare how much pressure you are using?"

After students have a procedure developed, a class discussion ensues to compare and contrast the procedures that individual groups have written and/or illustrated on their white-boards. Sharing each group's procedures has much value because students can see that while most everyone has the same general approach, some groups have identified more precise ways to assess the impact of differing pressure on the volume of air in the syringe. We return later to the importance of collaboration and sharing of ideas, and how this also reflects how scientists work. Before class ends, we ensure that all groups are prepared to begin working the following day as they enter the room.

Example of a Typical Student Procedure

1. Pull in 25-cc of air.
2. Cap the syringe and place it in the wood block.
3. Apply different amounts of pressure by pushing light, medium, and hard.
4. Record changes in volume as force increases.

The following day as students enter the room we remind them to begin working. No reason exists for waiting until the bell rings, and as other students enter the room they see their classmates working and do the same. This is just one way to increase on task-behavior and instructional time (Clough, Smasal & Clough, 1994). While students work, we take attendance and then begin actively monitoring the students to ensure safety precautions are met (e.g., wearing of shatter-resistant goggles and syringes secured in the wooden bases), and engaging students in conceptual discussions when appropriate. For instance, most groups use only one volume of air in their tests. So, we ask

- "How would your results change if you increased or decreased the original amount of air in the syringe?"

A question such as this keeps the students involved in the activity and mentally engaged in exploring the relationship between pressure and volume. Any off-task behavior is addressed by moving toward the offending group, asking what they have done thus far, and stating that we will stop back shortly to determine their progress.

When students complete their work, we spend some time discussing their results. We begin with a question such as

- "What did you notice when pressure was placed on the plunger?"

Students are often surprised the plunger was hard to push down. We follow this with

- "What is your initial thinking regarding how increasing the pressure/force on the plunger impacts the volume inside the syringe?"

Students always note that increasing the pressure appears to decrease the volume of air in the syringe. But we press further and ask,

- "What sort of procedure would be necessary to quantify this relationship?" or
- "How can we precisely determine what happens to the volume of air in the syringe if we double or triple the pressure/force on the plunger?"

Quantitative Investigation

After hearing students' initial ideas, we raise the issue regarding the benefits of having a standardized procedure for all groups to follow. To start the conversation we pose questions such as

- "What would be the pros and cons of all groups performing the same tests?" and
- "How are we going to decide what procedure to follow?"

Additionally, we can use this discussion to draw parallels between the students' work and how scientists need to develop procedures. We draw explicit attention to the nature of science by asking

- "How is this similar to what scientists do?" and
- "How might a standardized procedure be useful and detrimental for scientists?"

Other questions to scaffold students toward a standardized procedure include

- "How do we know all groups are applying equal pressure?" and
- "How much air should all groups place in the syringe at the beginning?"

This discussion helps students consider in more detail the specifics of their testing, and they develop a more accurate understanding of, and appreciation for, how scientific research is conducted. Importantly, the more stake students have in their procedure, the greater their interest is in ensuring all testing is done according to the standards they have set. Students now return to their testing and collect more precise force and volume measurements.

The third day is focused on reporting results, data interpretation and concept development, but be prepared for students to begin the class completing their testing. When testing is completed, students display their results on the class white board or on a computer spreadsheet projected onto a screen. We prefer using a spreadsheet so that the data from other classes can be easily included and compared. We now ask students how the large amount of data they have collected might be expressed to help us determine a relationship. Students quickly see that creating a graph would help, and the discussion now moves to determining what type of graph would be best for the kind of data collected and the question we are attempting to answer. For all student ideas, we ask for a rationale. We always make sure to record students' ideas on the white-board using the students' language, so that students know we value their ideas. After deciding upon a graph (a volume vs. pressure line graph is the clear choice of students), the class will reach the idea that as pressure increases volume decreases. We encourage students to summarize the conclusions from the lab in an overarching statement, a big idea using their own language. Only after the big idea statement is written on the board do we introduce the term "inverse relationship", stating that as the pressure on a gas increases, the volume occupied by that gas decreases.

Expanding Conceptual Understanding

After developing a "big idea" to describe the relationship between volume and pressure of a gas, we draw students' attention to the specific conditions required for this relationship to hold. For instance, we ask:

- "How did the amount of gas in the syringe (i.e., the molecules of gas, not the volume they occupied) compare before and after applying pressure?"
- "How do you think the temperature of the gas in the syringe compared before and after applying pressure?"

These questions are merely the beginning points to address that the relationship they are exploring between pressure and volume applies when the amount of gas and the temperature of the gas remains constant.

Students may think this relationship only works with air in a syringe. To help students realize the affect is universal, we utilize quick, full class demonstrations based on some prompts.

- "What do you think would happen if we started with a larger volume of air?"
- "How would this be different if we used a different gas?"

As students answer the aforementioned questions, we add their additional thoughts and statements to our big idea. Through this process of additional quick tests, each class produces a statement similar to the following:

Big Idea: *"For a constant amount of any gas at a given temperature, an inverse relationship exists between pressure and volume."*

Only after this kind of statement is developed by students, and when we are certain they understand it, do we introduce the name of this relationship and provide the mathematical statement (Boyle's Law, where $V_1P_1 = V_2P_2$). This is so that students conceptually understand the relationship and that the equation is merely a mathematical representation of that relationship. Later, when we begin addressing mathematical problems related to Boyle's law, we do not permit students to use the equation until they first conceptually consider the problem and speculate on what a reasonable answer would be. This is done to deter students from the plug-and-chug mentality when using mathematical equations.

For now, we return to our initial demonstration prior to the activity where we placed a crushed and tightly sealed soda bottle in a vacuum. We use scaffolding questions to build their understanding:

- "What happened to the volume of our crushed bottle in the vacuum?"
- "Given our big idea, what does that mean about the pressure in a vacuum compared to inside the soda bottle?"
- "How does the amount of air (i.e. number of molecules of air, not volume) inside the soda bottle compare before and after we turned on the vacuum pump?"
- "How then do you account for the crushed soda bottle expanding?"

After the connection between the big idea and the crushed soda bottle in the vacuum pump phenomenon is made, we have a nature of science discussion on how developing procedures and testing ideas are similar to what scientists do. We ask questions that explicitly draw students' attention to how they identified a problem, wrote an initial procedure, tested their procedure, identified problems with and modified their procedure, collaborated with others, analyzed data, and made many decisions throughout the process. Example questions include:

- "What did we do to determine the relationship between pressure and volume?"
- "We started in the lab, came together to discuss the results, and then went back to the lab. Why did we modify our approach?"
- "Why would a scientist modify their initial approach?"
- "How did the modifications help us answer the question?"
- "How do scientists' modifications help them?"
- "Given our work in this activity, why do scientists work with others and collaborate on projects?"
- "How is doing science like puzzle solving?"
- "How was our approach to investigating volume and

pressure of a gas like what scientists do when they study the natural world?"
- "What about doing science makes it far more of an interesting career than school science often portrays?"

Students' responses to these questions will vary. As they respond, we provide additional questions to help them understand that science is creative, social and non-linear. After the discussion is complete, we have students summarize the nature of science ideas in their notebooks. When students write down and summarize their ideas, they reflect deeply on the nature of science in relation to their laboratory experience and improve their written communication skills.

Conclusion

By putting laboratory experiences before concept development, students are better able to understand and internalize abstract scientific concepts presented in the classroom (Karplus, 1977). In this instance, we have taken a typical verification lab, made simple modifications such as open-ended questions and student invented procedures, and executed the lab before introducing the content. Modifications such as the ones implemented here are easy to make and provide students with concrete experiences to better account for how people learn (Clark, Clough, & Berg, 2000).

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