Using Story to Help Student Understanding of Gas Behavior

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ABSTRACT: Students tend to have a poor understanding of the concept of gas pressure. Usually, gas pressure is taught in terms of the various formulaic gas laws. The development of the concept of gas pressure according to the early Greeks did not include the concept of a vacuum. It was not for another 2000 years that Torricelli proposed that a vacuum can exist and that he was able to produce a vacuum above a column of mercury. However, the existence of a vacuum continued to be a contentious issue for at least another 100 years. During this time the behavior of gases was studied by Boyle, Amontons, Gay-Lussac, Daniel Bernouli, Charles, and Dalton. In the 19th century gas behavior was revisited and studied from the molecular level through the work of Graham, Maxwell, Boltzmann, and van der Waal. The stories of conflicting theories and the development of the concept of gas pressure gives students an increased appreciation for the nature of science and helps them with conceptual understanding of the concept of gas pressure.

KEYWORDS: story, teaching gas behavior.

Introduction

Conceptual knowledge of gas pressure is central to several high school chemistry topics, including stoichiometry of gaseous products and reactants, changes in state, kinetics and equilibrium. Understanding of the concept of gas pressure has been shown to be problematic for students (Benson, Wittrock and Baur, 1993; de Berg, 1995; 1992; Engel Clough and Driver, 1985; Rollnick and Rutherford, 1990; 1993; Séré, 1982; Stavy, 1988; Tytler, 1998).

It is generally accepted by chemistry educators that chemistry knowledge exists in three forms or levels of representation: (1) the macroscopic or the observable, (2) the sub-microscopic, molecular or the particulate and (3) the symbolic which is considered to be the language of chemistry, that is, the formulas, equations and mathematics (Gabel, 1999; Johnstone, 1991; 2000).

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Studies have shown that even though scientists are able to move freely between these different representations as they describe chemical phenomena, learners, especially novices, have difficulty interacting with chemistry concepts on these three levels (Chandrasegagaran, Treagust and Mocerino, 2007; Gabel, 1999; Harrison & Treagust, 2001; Reid, 2008). It is therefore expected then that students would have alternate views of gas pressure concepts because of their difficulty at describing the behaviors at the particle level.

Another issue with student understanding is the tendency for chemistry to become a series of formulas and equations that are recited but students are unsure what they actually mean (Bodner, 1991; Gabel, 1999). Many studies have been performed comparing algorithmic problem solving and conceptual understanding in which students are able to go beyond routine manipulations of variables.

Generally, chemistry knowledge involves the explaining of observable processes using particulate nature of matter and translating these explanations into equations for use in problem solving and communication (Johnstone, 1991). Kevin de Berg's (1995) research suggests that a qualitative approach to problem solving may reduce the dependence upon algorithmic problem solving and promote conceptual understanding.

School science

School science is mostly presented as factual knowledge as it appears in textbooks. The presentation as knowledge in its final form bears little resemblance to actual science. We should expect students to develop deeper understandings that allow them to generalize across diverse and relevant connections. To mediate such views of everyday science and "school science", it is recommended that teaching science become more contextual, enabling students to find more meaning and personal relevance in their science education. It has been shown that this deeper understanding can come through the use historical narratives. Michael Matthews (1994) suggests that teaching the concept of gas pressure provides an excellent opportunity for teaching using the historical contexts.

Ekstig (1991) suggests a teaching sequence accompanied by some activities for the historical development of the concept of air pressure. Chuck Biele, a high school teacher in Minnesota, has developed a lesson on the concept of air pressure and the vacuum entitled *"Sucking Students into Understanding Air Pressure and the Vacuum"*. The teaching of history often is in the form of short anecdotes in the absence of any struggles or controversy. For example, the invention of the barometer by Torricelli is often presented without reference to the political and philosophical opposition to the concept of a vacuum. According to Niaz and colleagues (2002) "it is essential that students be provided a glimpse of scientific practice imbued with arguments, controversies, and competition between rival theories/explanations" (p. 524). The presentation of historical contexts provides good examples of how conflict and controversy promote the development of knowledge (Brush, 1999; Niaz, 2005) and can improve an appreciation for the nature of science.

Methodology

Wandresee and Roach (1998) proposed the use of interactive historical vignettes (IHV) in the teaching of chemistry. These stories were both teacher and student-developed and were accompanied by various activities. They found that the use of IHVs were not only successful in helping students understand chemistry concepts but also increased their understanding of the nature of science. Heather Teller (2005), a Winnipeg high school chemistry teacher, in her Master's thesis used a series of ten historical interactive vignettes to help students understand the mole concept and increase their appreciation of the nature of science. These vignettes included 'Avogadro's Hypothesis', 'Faraday's Laws of Electrolysis' and 'Einstein the Chemist'. Based on this concept, I am suggesting the use of several interactive vignettes to use as a unit of study on gas behavior. The stories would be presented by the instructor or in the form of guided readings. Each vignette is accompanied by student activities and/or demonstrations with the objective of presenting a more historical and qualitative aspect of atmospheric pressure and gas behavior. It is expected that a more verbal less algorithmic approach to gas behavior will result in students acquiring a deeper conceptual understanding of gases.

The historical development of scientific understanding of gases can be divided into six topics:

1. The Atomists versus the Aristotelians: Much Ado About Nothing
2. The weight of the atmosphere (Torricelli to Boyle)
3. Pressure-Volume Relationships
4. Volume-Temperature Relationships
5. Pressure-Temperature Relationships
6. Particulate nature of gases (kinetic molecular theory)

The major sources of these vignettes are Middleton (1964), Shapin and Shaffer (1985), Conant (1952) and Brush (1999). The stories will be briefly outlined below.

Historically, the concepts of gas behavior were first described macroscopically, followed by particulate descriptions, the kinetic theory, and mathematical equations to describe the behavior. I am suggesting that this is the order to present these concepts.

1. The Atomists versus the Aristotelians: Much Ado About Nothing

The first set of stories describes the development of the concept of atmospheric pressure. It can be prefaced with a set of demonstrations or student activities. Students begin by placing an inverted beaker in a tub of water. The beaker full of air will not fill with water. Students can be drawn to the conclusion that air is matter and occupies space. They then invert a beaker full of water in a tub of water and slowly raise the beaker. Students will observe that the water does not empty until the beaker is raised above the surface of the water. Students will observe that air cannot enter the beaker until the water is evacuated. It appears as though nature prevents the formation of a vacuum. The question “What happens if the beaker is taller?” could also be posed, to be answered later.

Understanding the concept of atmospheric pressure requires students to first change their conception that air has no mass. The difficulty with the atmospheric pressure concept is the students must come to terms with air exerting a pressure of 101 000 Newtons per square meter or about 15 pounds per square inch. Simply telling students that we are used to it or it is balanced by our inner pressure does not make it any easier to accept.

Story of gas pressure begins with the conflict between Aristotle’s ideas and those of the atomist Democritus. Atomists maintained that matter was made of tiny particles and the spaces between these particles consisted of a vacuum, or nothing. Changes in density were a result of changes in how the vacuum was dispersed. The phrase attributed to Democritus is that "Nothing exists but atoms and the void".

Philosophically Aristotle could not agree with the concept of a vacuum. He maintained that the space around an object was occupied completely by that object. His support for this argument was using the concept of motion. He theorized that the motion of an object was dependent on the weight of the object and the resistance of its medium. He argued that an object would move instantaneously from one point to another in a void and there would be no difference in the motion of a heavy and light object.

Demonstrations of siphons, crushing cans, etc. can be performed to illustrate what was known to people of that time. Students should also be familiar with a water thief. Questions to pose are: What holds water in the straw when you put your finger over the end? What is crushing the can? How doe the siphon work? Students can also attempt to explain how a Hero's fountain works. They can also try to explain why they can drink through a straw in a stopper with two holes but not through a straw or tube in a stopper with only one hole that is not open to the atmosphere.

16th century miners were aware that water could not be pumped beyond about 34 feet. A series of pumps was required to raise water beyond 34 feet or 11 meters. It appears Galileo was the first to record these phenomena in his *Discorsi* in 1638, after hearing about it from his student Torricelli. The *Discorsi* were written at a time when the concept of atomism was considered atheistic and he hints that he may have entertained the possibility of a vacuum if it weren't for the unacceptability of the hypothesis. He does state that nature resists a vacuum to a height of 34 feet. He even determined that air had weight and water was 400 times more dense than air (water is actually 800 times more dense).

Gasparo Berti read the *Discorsi* and in 1641 constructed an experiment consisting of a long glass, tube, expanded into a small globe at the upper end, and the openings at either end could be closed by brass screws. The whole tube was filled with water and the lower end immersed in a tub of the same liquid. The water descended from the globe to stand in the tube at about 33 feet over the surface of the water in the tub. Unfortunately for Berti, the experiment was performed privately and publications relating to it were delayed and contradictory. Experiments were performed in the space above the water in the globe to confirm the presence of a vacuum, the results of which were not conclusive. At this time, Democritean atomism was as not popular, discouraging discussion and publication of the experiment.

Students can repeat the same experiment using hose and colored water in a stairway, school gym or outside a window (de Grys, 2003).

Questions to discuss are: What is "holding up" the water? What is in the space above the water? Students' replies are similar to the Aristotelians: air, water vapors, but a force keeping the water in the tube usually escapes them.

2. Weight of the Atmosphere

Evangelista Torricelli had been a student of Galileo's and never accepted his explanation for the inability to pump water beyond 34 feet. He felt it was the weight of the atmosphere that was the limiting factor. He chose to use mercury, because it is 14x more dense than water, to test his "ocean of air" hypothesis. In 1643, Torricelli constructed a glass tube about a meter long, filled it with mercury and inverted it into a bowl of mercury. He found the mercury rested at a height of about 76 cm above the height of the surface of mercury in the bowl. The height of the mercury did not change with moving the tube side to side or with the shape of the tube. However, Torricelli thought he had failed to demonstrate the weight of air because the level of mercury tended to fluctuate with changes in the weather.

There was much opposition to Torricelli's hypothesis that a vacuum existed above the mercury in the tube. In an effort to demonstrate the presence of a vacuum he filled the bowl with water above the mercury. When he slowly lifted the tube it filled with water, establishing that nothing was above the surface.

Torricelli wrote Michelangelo Ricci about the results of his experiments and Ricci began to spread the word of the vacuum and weight of air. In all this, Berti's work was ignored. Ricci passed on Torricelli's work to a publicist in Paris, because France was more tolerant to the idea of a vacuum than Rome. It was in France that the concept of vacuum was carefully scrutinized.

Arguments against the presence of a vacuum included:

- the mercury gives off spirits that pushed the mercury down in the tube
- the space was filled an ether that travelled through the glass

Initially, even Blaise Pascal was unwilling to accept the vacuum theory. He repeated Torricelli's experiments and became convinced of the presence of a vacuum.

Pascal hypothesized that if Torricelli's "ocean of air" hypothesis was true, then the weight of the atmosphere would decrease with increased altitude. 1648, Pascal convinced his brother-in-law, Florin Perier, to take the barometer up the mountain Puy de Dome and take measurement of the height of the column of mercury along the way. Pascal's prediction was correct. Detractors were now willing to accept the "ocean of air" theory, but not the presence of a vacuum.

In 1650, Otto von Guericke developed the first air pump. In 1654 he used it in his famous Magdeburg demonstration. He used it to evacuate the air from two small hemispheres. 2 teams of 8 horses could not pull the hemispheres apart!

This experiment can be replicated by purchasing a set of Magdeburg hemispheres or using two suction cups. Students can be asked what holds the hemispheres together.

von Guericke postulated that the weight of air was holding the hemispheres together. This demonstration helps students observe that air pressure is not just a downward force.

In an effort to finally end the debate on the existence of a vacuum, Robert Boyle asks Robert Hooke to construct an air pump. He performed what he called Experiment 17. He placed a mercury barometer into a container and attached the air pump. When the air in the container was removed, the column of mercury fell. He felt this was definitive evidence that the weight of the air held up the column of mercury. Franciscus Linus (aka Francis Line) and Thomas Hobbes disagreed and proposed the Funicular Theory. They theorized that there was an invisible rope, called a funiculus that held up the mercury.

Students should begin to understand that atmospheric pressure is a force related to the mass of a column of air that can act in more than a downward direction. The issue of conflict and controversy can be explored.

3. The Relationship Between Pressure and Volume of a Gas

Once atmospheric pressure has been discussed, instruction can move to the gas laws. Traditional textbook instruction of the gas laws includes a simple discussion of the scientist and their experiments followed by the equation that describes the law but without any hint of a controversy, competition or conflict. A particulate explanation may be provided, but the objective is still to solve the mathematical problems at the end of the chapter. Students can be introduced to gas laws through demonstration, experiment and stories of the historical discoveries of the relationships. Problems should be solved conceptually and qualitatively (deBerg, 1995) before mathematical calculations are attempted.

Pressure-volume relationships can be discovered by the students using various common lab activities or demonstrations. This can be followed by the story of Boyle's experiment and a discussion including the contributions of others. In an effort to study the elasticity of gases, Robert Boyle constructed a J-tube and trapped a gas in the end with a column of mercury. He noted that as he added mercury, the volume of the gas was reduced. He recorded the data in tabular form and concluded the relationship was reciprocal. Interestingly he did not graph the data, nor use it in a calculation (de Berg, 1990).

Edme Mariotte used trapped gas in a Torricellian tube to test his hypothesis on the effect of increasing weight on the volume of a gas. The difference in the two methods is Boyle's extrinsic desire to refute the funicular theory while Mariotte's is the desire to answer an intrinsic question (de Berg, 1990). Boyle published his experiments, including a table of data in 1662, while Mariotte did not publish his results until 1676. Despite this the relationship between pressure and volume is still attributed to Mariotte in France. Students can develop arguments for who deserves credit for the discovery.

4. The Relationship Between Temperature and Volume of a Gas

Students can then be introduced to volume-temperature relationships using common lab activities, simulations and demonstrations, followed by the historical story of its discovery. Bakers since the dawn of civilization have known about the relationship between temperature and volume. After all, heating a gas in a cake or bread makes the cake or bread rise more. But the precise textbook relationship, $V/T = k$, was not described until 1699, when it was discovered by the French physicist Guillaume Amontons. Amontons developed a thermometer that used the increasing volume of gas with temperature instead of a liquid. In 1702, he measured temperature in terms of proportional changes in pressure. Robert Boyle also studied the relationship between temperature and pressure, but like Amontons, failed to discover what we call Charles' Law because a temperature scale did not exist.

In 1714, Daniel Fahrenheit invented the mercury thermometer and the temperature scale that is named after him. He proposed 0 to be the coldest temperature in Western Europe and 100 being the highest temperature. This made the freezing point of water 32°F and the boiling point of water 212°F.

In 1742, Anders Celsius invented the centigrade temperature scale that is often named after him. He used the freezing point of water as 0°C and the boiling point of water as 100°C.

Amonton's experiment was repeated much later by Jacques Charles in 1787, and much, much later by Joseph Gay-Lussac in 1802. However, Charles did not publish his findings, but Gay-Lussac did. The relationship is most frequently called Charles's Law in the British sphere of influence and Gay-Lussac's Law in the French sphere but it was never called Amonton's Law!

Jacques Charles, a French scientist, only had a basic knowledge in mathematics and almost no science education. He became interested in non-mathematical, experimental physics when Benjamin Franklin visited Paris in 1779 as an ambassador for the new United States. With the popularity of hot-air balloons in his time, investigated the expansion rates of different gases due to temperature changes. He used an apparatus very similar to that of Boyle. He took gases trapped in J-tubes and immersed them in water baths with varying temperatures. Regardless of the gas tested, he found that for every 1 degree Celsius change, the volume changed by a factor of 1/273. When the temperature was increased by 273°C, the volume doubled. Once again students can develop an argument for who should receive credit for the discovery of this law.

5. The Relationship between Pressure and Temperature of a Gas

Similarly, pressure-temperature relationships can be introduced. Joseph Gay-Lussac carried on Charles' work and discovered the relationship between temperature and gas pressure. Gay-Lussac was sent to a boarding school in Paris where he became an assistant to Claude Louis Berthollet. Berthollet took a young Gay-Lussac under his wing and trained him in chemical research. In the winter of 1801-1802, Gay-Lussac performed his first independent experiment: the thermal expansion of gases, a repeat of Charles' discovery.

Gay-Lussac became well known for his dedication to meticulous experimenting, as a result he observed more consistent and reproducible results than Charles. As part of his studies on the expansion of gases, Gay-Lussac determined that if the volume and the amount of a gas are held constant, increasing temperature of a gas will increase the pressure.

Students can extrapolate their data from temperature-volume experiments or temperature pressure activities to zero pressure or volume in order to derive absolute zero. Students could provide arguments for the validity of these laws under all conditions. Students don't usually find compressing a gas to zero volume problematic (Schmidt, 1997), unless they view gases from a particulate level.

6. Why Do Gases Do What They Do?

In order to understand the concept of gas pressure, students must understand the behavior of gas particles. The historical context of the particulate explanations of gas behavior will be outlined briefly.

Gas behavior was initially described by the lattice theory of gases which was generally accepted between 1770 and about 1860. It was held by scientists such as Newton, Dalton, Ampere and Avogadro. The repulsive forces of gas particles caused pressure on containing vessels. Students tend to hold a similar view (Brook, Briggs & Driver, 1984; Novick & Nussbaum, 1981).

In the 18th century, Daniel Bernoulli showed that the pressure is proportional to the kinetic energy of the particles. Bernoulli's theory introduced the idea that heat or temperature could be identified with the kinetic energy of particles in an ideal gas. Bernoulli's work was generally ignored and he never continued with his work on kinetic energy; Brush suggests that this may have been due to the absence of a "gadfly" (Brush, 1999).

In 1857, Rudolf Clausius made several key assumptions about gases, including large empty spaces between the gas particles and intermolecular forces are very small. Using these assumptions he was able to calculate the velocity of several molecules. Critics pointed out that if the particles were moving so quickly, diffusion would occur much faster. Clausius saved his theory by proposing a new variable that determined the average distance a particle could travel before encountering another molecule. Clerk Maxwell used this variable in his kinetic theory. Using Newtonian mechanics to describe molecular motion, Maxwell determined that the root mean square velocity of a molecule was a function of the temperature and the mass of the particles.

Prior to Maxwell, the kinetic theory assumed all particles at the same temperature would have the same speed. But Maxwell's kinetic theory proposed that the collisions between molecules would result in a statistical distribution of speeds. Ludwig Boltzmann published a kinetic theory that resulted in a statistical distribution of velocities with the most molecules moving at an average velocity.

Finally, Johannes van der Waals said the assumptions made in the kinetic theory and idealized gas laws were not correct, since at low temperatures and high pressures gases condense. In 1873 he published a famous equation that modifies the gas laws to account for forces of attraction and the size of molecules. The law brings the understanding of gas behavior from idealized to what are called "real gases".

Using the particulate nature of matter and the kinetic molecular theory students can revise answers given to previous questions. Students should now be guided to develop explanations of gas behavior, limitations of the gas laws and the concept of idealization.

Conclusion

Teachers do not tend to regard the outcomes involving the history and nature of science as highly as the 'traditional' learning outcomes (Lederman, 2006) because they do not believe that the inclusion of the history of science adds to the normally assessed knowledge and skills of students (Monk & Osborne, 1997). They find the history of science as a group of nice stories that add a human face to science concepts but do not use the history of science to teach scientific concepts. Compounding the problem, textbooks often reveal a biased version of history of science by over simplifying the science stories and trying to fit them into the concept, rather than dealing with the concept in the context of the history (Matthews, 1994). The history of science presented in this manner tends to contribute to myths students and teachers often believe (Allchin, 2003; Milne, 1998; Niaz, 2007).

A unit on gas behavior can be presented as a series of interactive historical vignettes, in which the concepts are embedded in the historical contexts. Fensham (1994) has shown that teachers can improve their instruction and students' understanding can improve through the use of historical contexts. Through story, students learn the concepts in a verbal, qualitative manner rather than a series of mathematical algorithms. Teachers often do not have the time to research the historical contexts and create learning experiences to accompany instruction. The development of a unit of study for teachers helps them to understand the contexts and modify the stories and activities to align with their own experiences, making learning a richer experience for both teacher and student.

Presentation of a history of science that excludes conflict, controversy and competition challenges students to critically examine societal issues (Apple, 2004). Students will also see how their conceptions are similar to others and how their struggles are the same as those of important scientists. Other benefits to this approach include students will recognize

- the development of concepts are not necessarily linear
- the human element is responsible for development of concepts
- science knowledge is not seen as in its final form

- the importance of dialogue, conflict and criticism in the development of science concepts
- the dependence of one concept upon another
- the importance of experiment and hypothesis
- the importance of idealization

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