Causal Patterns in Air Pressure Phenomena

Lessons to Infuse into Pressure Units to Enable Deeper Understanding

The Understandings of Consequence Project
Project Zero, Harvard Graduate School of Education

This module was created by Belinda Basca and Tina Grotzer with assistance from many talented individuals. David Perkins provided insight into the nature of the causalities involved. Dorothy MacGillivray contributed to the design and substance of the module. Rebecca Lincoln provided invaluable editing and advice on content. Melanie Pincus assisted in analyzing the data that we collected on teaching the concepts in these lessons. Sarah Mittlefehldt and Rebecca Lincoln helped to test the lessons with students and Regina Ritscher helped to analyze students' interviews to assess their understanding. Sun Kim and Becky DeVito assisted with editing and assembling aspects of the design. Carlos Vasco, Professor Emeritus of Mathematics, at the National University of Colombia at Bogata, and Joseph Snir, Physics Education Professor at the University of Haifa, Israel, advised us on matters of science and we thank them for their patience with our many questions and their good humor in finding ways to explain complex concepts so that students could grasp them. Bruce Campbell also helped with a number of science-related puzzles. Any errors or omissions are the sole responsibility of the authors. We are immensely grateful to Nora Sabelli, Ken Whang, and Elizabeth Vanderputten at the National Science Foundation for their support and guidance. The teachers in the Burlington, MA Public Schools, specifically Rich Carroll, Lucy Morris, Valorie Tobias, and David Thibault worked with us to test the concepts with their students. We are very grateful to them for their patience and insight. We thank the administration, particularly Dr. Bill Conners and Mr. Richard Connors, for supporting our work. We also thank the many students who shared their thinking with us over the past six years.

Explanation of Photographs on the Cover

The shape of a *balloon* results from the balance between inside and outside pressures surrounding the balloon, a type of *relational causality*.

Hurricanes are caused by a combination of atmospheric factors. One of the most important is an air pressure gradient: an area of low pressure at the center of a storm draws air from areas of higher pressure towards it, creating strong and destructive winds. (*Photo Credit: National Oceanic and Atmospheric Administration/Department of Commerce.*)

The flight of an *airplane* is explained by the *relational causality* involved in Bernoulli's principle. Faster moving air over the curved surface of the top of the wing exerts less air pressure than that traveling over the relatively flatter surface of the bottom of the wing, resulting in a pressure differential that produces lift.

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INTRODUCTION

This introduction provides an overview of the module. It gives a rationale for why it is so important to teach the causal concepts presented here in order to develop a deep understanding of air pressure phenomena. It makes suggestions for how to encourage a classroom culture that supports the development of the understanding goals of the module.

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The shape of a *balloon* results from the balance between inside and outside pressures surrounding the balloon, a type of *relational causality*.

Introduction

Overview

This curriculum module consists of nine lessons to infuse into a broader unit on pressure. The lessons are designed to address persistent difficulties that students have when learning about air pressure. These difficulties stem from how students reason about the nature of cause and effect.

The module is formatted as follows: there are three sections. Each section introduces one of three ways of thinking about causality that students need to master in order to develop a deep understanding of air pressure. The sections, and the multiple lessons within each section, are sequenced to build understanding. For each lesson, background information describes the difficulties that students typically have in learning about air pressure, and how each way of thinking about causality is important in addressing the difficulties. Each lesson includes subject matter goals and more general goals about the nature of causality. This module is designed for middle school, but can be adjusted for use with younger and older students.

Embedded within the lessons are special activities called RECAST activities. These activities are designed to REveal CAusal STructure, or help students RECAST their understandings so that they fit with the causal patterns that scientists use. RECAST activities have outcomes that don't fit with what students typically think, so they may serve as an impetus for students to restructure their understandings.

The curriculum is designed around "best practices" in science education. Lessons involve students in inquiry-based activities that ask students to observe and construct understandings. Lessons typically begin by asking students to examine their current beliefs, and invite opportunities for students' ideas to evolve during the course of the unit. Student discussion is a central activity and teachers are encouraged to create an environment where students are comfortable sharing their ideas. Through discussion, students will realize that science involves revising ideas in a process that leads to the best explanation of the phenomenon in question.

Challenges in Understanding Air Pressure

Pressure is defined as the force per unit of surface area, where the force is applied perpendicularly to the surface area (Pressure = $^{Force}/_{Area}$). Air pressure is the collective result of the molecules that make up the air bouncing around and applying forces against any surface with which they have contact. The effects that we notice and attribute to air pressure are the result of balances and imbalances between air pressure in different areas or inside and outside of objects. For instance, an inflated ball remains inflated because the air pressure inside the ball is equal to or balanced with the air pressure outside the ball.

Why are concepts related to air pressure so difficult for students to understand? Many of the difficulties students have stem from assumptions students make about the nature of causes and effects that are very different from those that scientists make. These assumptions make it difficult for students to develop a deep understanding of air pressure and air pressure-related phenomena.[1]

This module introduces three causal forms that help students understand air pressure-related phenomena. These include recognizing and understanding: 1) non-obvious causes; 2) passive causes; and 3) relational causality. Understanding these causal forms influences students' ability to grasp a variety of pressure-related concepts such as weather patterns, Bernoulli's principle, and "vacuum" pumps, to name a few.

Non-obvious Causes

Scientifically accepted explanations often involve causes that are hard to notice. You can't observe the causes directly; you have to figure out that they exist. Many of the science concepts that give students difficulty involve non-obvious variables. For instance, students have difficulty reasoning about density (an intensive quantity),[2] microbes and microbial recycling in ecosystems,[3] and the process-like behavior of electrons and protons in electrical circuits, to name a few.[4] Students need to know that causes can be hard to notice, or even impossible to see, so that they don't limit their search for explanations to obvious variables.

Air pressure is a non-obvious variable. It was not formally recognized until 1643 when the mathematician Evangelista Torricelli discovered that air pressure accounted for the height to which water could be pumped out of mineshafts.[5] So it is no surprise that students and laypersons often fail to note air pressure's existence or contribution to an effect. Research shows that students ranging from 6 years old through university level fail to recognize air pressure when engaged in science activities focused on it.[6] Students have difficulty shifting their focus from the apparent features of the task to less obvious variables, such as the behavior of air or water. Students' perception of how gases behave differs from that of scientists;[7] and they have difficulty understanding gases and their role in air pressure.

Air is around us all of the time, so we are accustomed to the presence of air pressure. Beyond this, our bodies continually adapt to the sea of air in which we live. We are usually unaware of our bodies' adaptations; they only become obvious when air pressure changes rapidly, such as when our ears pop in an ascending airplane. When students are not aware of air pressure as a possible cause, they typically turn to concrete, obvious variables to try to explain pressure-related phenomena. For example, when asked why a balloon partially deflates when driving from higher to lower altitude, most students speculate about the possibility of obvious variables, such as a hole in the balloon, rather than changes in non-obvious variables, such as air pressure.

One way to help students recognize the existence of air pressure is to find ways to make its effects obvious. For instance, research has found that high school students do realize that the pressure of enclosed air in a syringe increases with compression.[8] This is not startling since students feel the effect of the increased pressure on their hands. The effect is obvious. When the syringe was not compressed and they could not feel an effect, 70% of students thought the enclosed air did not have air pressure. Other research showed that 11- to 13-year-olds could not imagine air pressure without some type of movement associated with it.[9] They considered equilibrium situations to be due to a lack of air pressure rather than due to equilibrium between pressures.

Passive Causal Agents

Closely related to the issue of the non-obviousness of air pressure is that of passive causal agency. When we envision causality, most of us picture some type of action leading to some type of effect. In this image, the cause is seen as active—it does something that leads to a result. However, some forms of causality do not neatly fit this image. Instead, they bring about outcomes (sometimes obvious and sometimes not) in ways that one might call passive. What do we mean by this? Here are some examples:

- An arch bridge is a feat of balanced forces. The stones that make up the arch distribute the weight around the half circle and the abutments maintain the shape of the half circle. The structure and resulting balance of forces causes the bridge to stay up. However, no active movement is associated with the outcome. If one of the abutments were to be removed, the role of the abutment in maintaining the arch and distributing the forces to keep the bridge up would become dramatically clear. However, we don't typically think of the abutments as "causing" something.
- When riding in a car at fifty miles per hour, everything in the vehicle is moving at 50 miles per hour, including us. The car has brakes to stop it. What stops us? Well, as long as the stopping of the car is gradual, we might not notice the role that our seatbelt plays in helping to stop us. It is a passive restraint system. When a car stops very hard (amplifying the effect), we are more likely to recognize our seatbelt as a cause that keeps us from lurching forward each time the car stops. A more active causal agent would have a greater chance of being recognized. For instance, if a hand came out of the dashboard and pushed passengers into their seats each time the car came to a stop, we would quickly recognize it as a causal factor in the system.

Passive causal agents are not easy to notice. They typically don't draw attention to themselves by dramatic outcomes. For instance, in the bridge example, the balanced forces just continue keeping the bridge up. The effect isn't noticeable; you could say that we take it for granted, and in this way, passive causes can be non-obvious. In the case of the bridge, the system is balanced. Passive causes are difficult to detect, unless the system is made active by disrupting its balance. We typically attach causality to events, so if the bridge fell down, we would say that something caused it to collapse, but we typically fail to realize the causes in play when the bridge stays up. When an event does occur, students typically look for active (and therefore more obvious) causal agents.

How does passive causality complicate matters for students? First, students are unlikely to recognize air pressure-related phenomenon that are not "event-like." Second, when they do attempt to reason about air pressure, they are likely to characterize it as an active causal agent—substituting notions of force for pressure. Let's consider each issue in turn.

Air pressure is an ambient variable that is typically always present. When air pressure is balanced, it doesn't appear to "do" anything. However, when the balance shifts, it results in events or changes (ears popping, balloons expanding, liquid rising, and so on) that make it appear active. Analogous to the bridge example above, disrupting the balance of the system results in a dramatic event that fits with students' expectations about what constitutes a cause and effect relationship (that something acts on something else to make something obvious happen).

Students typically characterize air pressure as an active push in one direction, a unidirectional force that pushes down. This could result from substituting a force conception for pressure. Or it could be a natural extension of students' understanding of pressure as the force per unit of surface area, where the force is applied perpendicularly to the surface area ($\text{Pressure} = {}^{Force}\!/_{Area}$). However, air pressure acts omni-directionally. Because particles are moving in all directions, every direction that we choose for a unit of surface area will have particles that hit it perpendicularly. Visualizing this requires students to take the simple case of one surface and extend it to all the possible surfaces that molecules could bounce off of. This is cognitively challenging!

In order to grasp that air pressure acts omni-directionally, students also have to realize that molecules that make up the air can bounce in all directions, not just down. Students often draw their models of air pressure unidirectionally, with pressure arrows pointing downward. They tend to think of air pressure as "pushing down on them" similar to the way they think of gravity pulling them towards Earth's surface. This is evident in students' conceptions of air pressure, and particularly recurrent with water pressure. As with air pressure, the idea of water pressure existing equally in all directions is counter-intuitive to students.[10,11]

Pressure acting in a greater downwards direction than in a sideways one is more appealing to students. Even physics textbooks use terms that reinforce students' original erroneous conceptions of pressure.[12] To further complicate matters, when students include other variables, such as gravity and the density of molecules that make up the air, in the equation, it reinforces the notion that air pressure must push down because it is subject to gravity. Without knowing how to factor the relative potency of the variables involved, students don't know how to reason their way out of these understanding traps.

One further source of students' confusion may generate from reasoning about air pressure related phenomena at different levels. We do speak of individual molecules that make up the air as forceful—bumping into and bouncing off of things. The ambient, omni-directional aspects of air pressure are due to the collective effect of individual molecules colliding and bouncing around. It is well documented that students have difficulty reasoning about collective behaviors, and moving back and forth between levels of individual interaction and collective, emergent outcomes.[13] The problem can be cast in terms of reasoning about decentralized (or emergent) rather than centralized causes. A centralized cause typically has one agent that is primarily responsible for an outcome, for instance, one motorized floodgate that opens or closes to control water flow. A decentralized cause typically emerges from the behavior of many individual agents that behave according to individual rules, for instance, individual ants in an anthill pre-programmed to act in certain ways that ultimately give rise to the overall anthill organization. In the case of pressure, while molecules that make up the air bounce around and can be individually thought of as forceful and centralized, the collective behavior is ambient and decentralized. It can be difficult for students to coordinate these different characterizations when relating what happens at a molecular level with what happens at a collective level.[14]

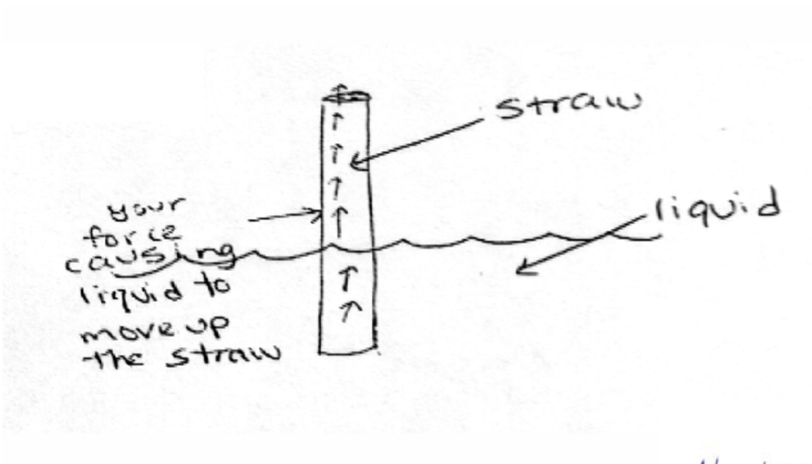
Students' difficulties in understanding the passive, omnidirectional nature of pressure are particularly evident when students are learning about hurricanes. Even if students learn that winds are the result of air moving from areas of higher pressure toward areas of lower pressure, the wind moves in a specific direction and therefore, exerts force in that direction. Hurricanes have powerful winds and therefore indelibly imprint a forceful, unidirectional notion in students' minds. Students confuse the forcefulness of the direction of the winds with the omnidirectional, pressure-related cause of the wind. Hand in hand with this idea is the notion that faster moving wind is more powerful and therefore must exert more pressure (which directly contradicts Bernoulli's principle).[15]

Relational Causality

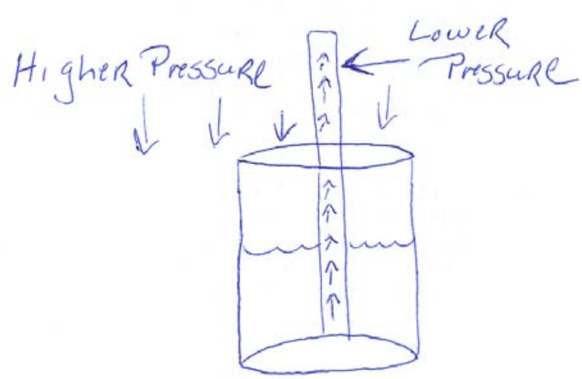
Many pressure-related concepts are explained by a relational pattern of causality. This means that an outcome is due to the relationship between two variables, either an equilibrium relationship or a differential between two variables (in this case, higher and lower pressure). Neither variable alone is the cause; instead, the interaction of the two must be considered. Contrast this with a simple linear model where one event directly causes a given outcome. A linear causal model is unidirectional and involves a one to one correspondence between causes and effects.[16]

Students typically use linear causal models to explain pressure-related phenomena. Research found that half of the 12-, 14- and 16-year-olds surveyed explained drinking from a straw in terms of pressure or a vacuum actively *sucking* or *pulling*, rather than a pressure differential between a lower pressure inside the straw and a higher pressure outside the straw as the cause of the event.[17] (See graphics below.) The linear causal model has salience for students, perhaps because they view themselves as taking an active role in drawing the liquid through the straw.

An awareness of non-obvious causes and passive causal agency has the potential to move students towards a relational understanding of pressure-related phenomena. However, because simple linear causality is much easier to grasp and because most students are not familiar with relational causality, recognizing non-obvious and passive causes is not enough. Students benefit from explicit opportunities to learn about relational causality and discuss its role in pressure-related phenomena.[18]



Linear Model:
"Sucking creates a vacuum in the straw that causes the liquid to go up it." –8th grader



Relational Model:
"When you drink from a straw the difference in the pressure inside and outside of the straw causes the drink to go into your mouth. When you suck on the straw, you draw air molecules from within the straw; the less dense air provides less pressure, especially compared to the air pressure outside of the straw. So the higher air pressure outside pushes the drink down deeper into the cup in the direction of the straw, and since that's the only opening the drink goes up the straw and into the mouth." –8th grader

The examples above are about drinking from a straw. Students tend to reason linearly—you suck and it pulls the liquid into your mouth. Scientists reason relationally—removing some air from the straw lowers the air pressure in relation to the (now) higher atmospheric pressure, so that the liquid is pushed into the straw.

Breathing can also be described by relational causality. As you press upward on your diaphragm, the pressure inside your lungs is higher than the outside pressure and air flows out of your lungs. As you pull down on your diaphragm, the pressure inside your lungs is lower than the outside pressure and air flows into your lungs. Similarly, with a balloon, the pressure in the balloon is *pushing out* AND the pressure outside the balloon is *pushing inward* to give a balloon its shape. The balloon remains inflated because the air pressure inside it is equal to, or balanced with, the air pressure outside of it. Let's define the outside air pressure to be P_o, and the inside air pressure to be P_i. When the outside air pressure (P_o) = the inside air pressure (P_i), the pressures are balanced.

Often, however, instances occur which disrupt this balance with noticeable results. If you add more air to the balloon, it will inflate. Why? You need to look at it from two standpoints. First, consider what is happening inside the balloon. There are molecules that make up the air moving around quickly and bumping into the molecules around them. When you add more air to the balloon, you're adding more molecules, which do more bumping—therefore the force increases. Next consider air pressure outside of the balloon. It remains the same. This creates a pressure differential between the inside and outside of the balloon. Pressures always balance out (unless there is something preventing them from doing so, such as a lid on a jar). Thus the inside air pressure must change to be in equilibrium with the outside air pressure. How does it do this? The additional force within the balloon spreads out over a larger area. Remember that $P = F/A$.

In order for it to be in balance—and thus reach equilibrium—and for P_o to equal P_i, the area of the balloon has to increase. The area increases (air pressure decreases) until equilibrium is reached between the inside and outside air pressures, with the result of a bigger balloon. If the area did not increase, the air pressure inside the balloon would increase because a larger force over the same area would result in a larger air pressure.

Other Challenges in Learning to Understand Air Pressure

This module introduces barriers to understanding air pressure that relate to how students think about the nature of causality. However, in our work with students, we have noticed other points of confusion in learning to reason about air pressure. For instance, students often take higher altitude to mean higher pressure, rather than lower pressure. While the confusion seems to be based more in linguistics than scientific understanding, it results in errors. Some of the confusions have to do with very basic concepts about the nature of air, for instance that it is matter and that it takes up space. Further, some of the activities that are typically part of pressure units can play into students' confusions. For instance, students think of air pressure as only pushing downwards. Activities such as the "bed of nails" (where someone, usually the teacher, lies down on a bed of nails) can be very effective for helping students understand the difference between force and pressure. However, the activity shows pressure, not air pressure and in helping students map its relevance to air pressure, there should be an explicit discussion of how pressure in this instance if different from air pressure. Issues such as these arise in any unit and with any activities. What's important is that teachers are alert to the sense that students are making and help students navigate around potential misunderstandings through discussion and targeted learning opportunities.

Summary

In summary, it is likely that your students' ideas will fall along a continuum of those presented here for each aspect of causality. A goal of this curriculum is to help students learn to reason about these three aspects of causality—non-obvious causes, passive causal agency, and relational causality—so that they can grasp the scientifically accepted explanations for pressure related phenomena.* Often, understanding one of these aspects supports understanding of the others; for instance, recognizing the non-obviousness of air pressure can bring students around to the relational model. If this happens with your students, they might see overlap within these lessons. Through the activities in this module, all students should make some progress towards models of air pressure that have greater explanatory power.

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*From a philosophical stance, it should be recognized that some scientists refrain from attaching causality to concepts such as pressure that define parameters specifying the state of a system. They are more likely to talk about "how" a system behaves than "why" certain events take place and to focus on defining the laws to make it possible to predict what will happen. According to Physics Education Professor Josef Snir, rather than "pressure as a cause to different phenomena, pressure is a parameter that the scientific community defined in order to formalize rules and regularities in that set of phenomena." According to physicist Lester Chen (personal communication, April 30, 2003),

> "The [little-known] nature of physics is that everything must be taken on a matter of faith. We [physicists] often talk about 'laws of nature,' but really, they are just descriptions or rules that we have come up with to describe the phenomena we observe. However, just because the rule described the last X experiences, that does not guarantee there is not another one coming up that proves the rule wrong (e.g., the often quoted theory of the ether). So, in the end, we are left with wondering "Why are the rules the way they are?"... There can be no satisfactory answer to this question. So, I prefer to stop the 'Whys' at the level of the rules."

Contrary to this stance, we do use causal language throughout this module and others. Our research shows that students bring and apply assumptions to their learning that are causal in nature and that these assumptions generate problems in developing deep understanding of the science concepts. Given that students already view the problems through a causal lens, we seek to substitute their problematic assumptions with ones that yield a better understanding of the science. Our research shows that doing so benefits students' understanding (of the concepts, if not the epistemology). Ultimately, it is our hope that those students who go on to study physics at the university level will have the opportunity to learn finer epistemic points about the nature of knowing in physics.

Instructional Approach

The activities in this module are best supported by a classroom culture that fits with the following suggested actions:

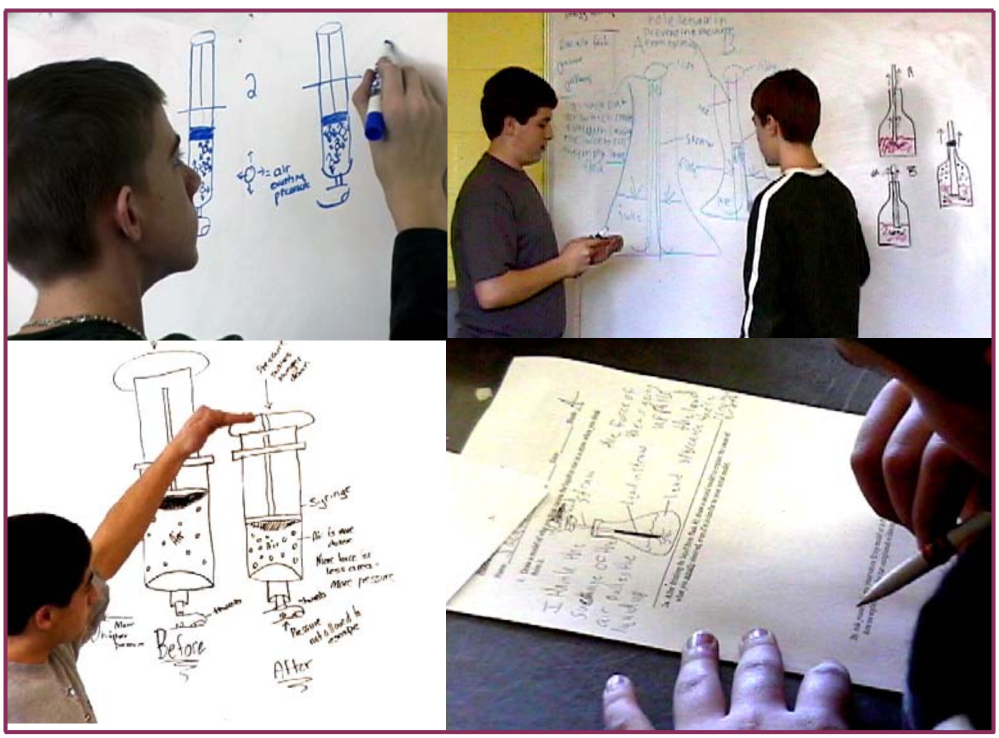
- Encourage students to take risks in their thinking and to test their ideas in a social context. No ideas should be shot down. Instead, relevant evidence should be considered.
- Encourage students NOT to accept ideas just because someone else believes them. Students should change their ideas when they find that the evidence is convincing.
- Recognize that students' most challenging questions can invite conceptual change. Use these questions to help students perceive the need for more sophisticated models.
- Emphasize developing understanding and the importance of transferring understanding to new contexts as opposed to *right answers*.
- Seek opportunities to engage students in scientific inquiry, and try to create learning opportunities that mimic the process of scientific discovery. However, not all learning can be inquiry-based or constructivist. Students also need exposure to the models that scientists have evolved during centuries of scientific inquiry.
- Recognize that students come to class with general principles about how the world operates as a result of their own attempts to make sense of the world. Offer opportunities for them to reflect on their own thinking.
- Encourage testing and revising one's thinking over *getting it right*. Students who adopt the *right* model without deeply reasoning it through are likely to revert to their less evolved models as soon as the unit ends.
- Help students to realize that no model explains everything about a particular phenomenon. Each model fits in some ways and doesn't fit in others. Critique models as a regular part of classroom discussions. Some models have more explanatory power than others, but no model captures the whole idea.
- Encourage students to generate "rival models" as often as possible. Rival models are two different ways of explaining the same event. Beginning with two different models can help students view the models more flexibly and keeps them from becoming overly invested in one model. However, acknowledge that students sometimes have a firm explanation and need to grapple with it.
- Expect that your students will move through various understandings and models towards a more scientifically accepted explanation. They may not all accept the scientific model before the end of the unit. Science involves the systematic discard and revision of models towards the goal of developing ones with greater explanatory power. Understanding evolves in a similar manner.

Having Students Model Their Ideas

Throughout this module, students are asked to model their ideas. This is a critical part of the pedagogy of the unit and it serves multiple purposes:

- It helps students get in touch with their own thinking.
- It helps students become invested in the questions under consideration.
- It helps each student prepare his or her ideas so that he or she feels more prepared to participate in the group discussion.
- It helps teachers be aware of what students are thinking.
- It helps teachers and students see how students' ideas evolve over the course of the module.
- It underscores the importance of coming up with increasingly explanatory models. Scientists critique and discard models in an effort to find those models that have the most explanatory power. Students learn an important lesson about how knowledge is generated in science.

The teachers who tested this module had students create models in their journals, on individual whiteboards, on paper, and on the whiteboards in front of the class.



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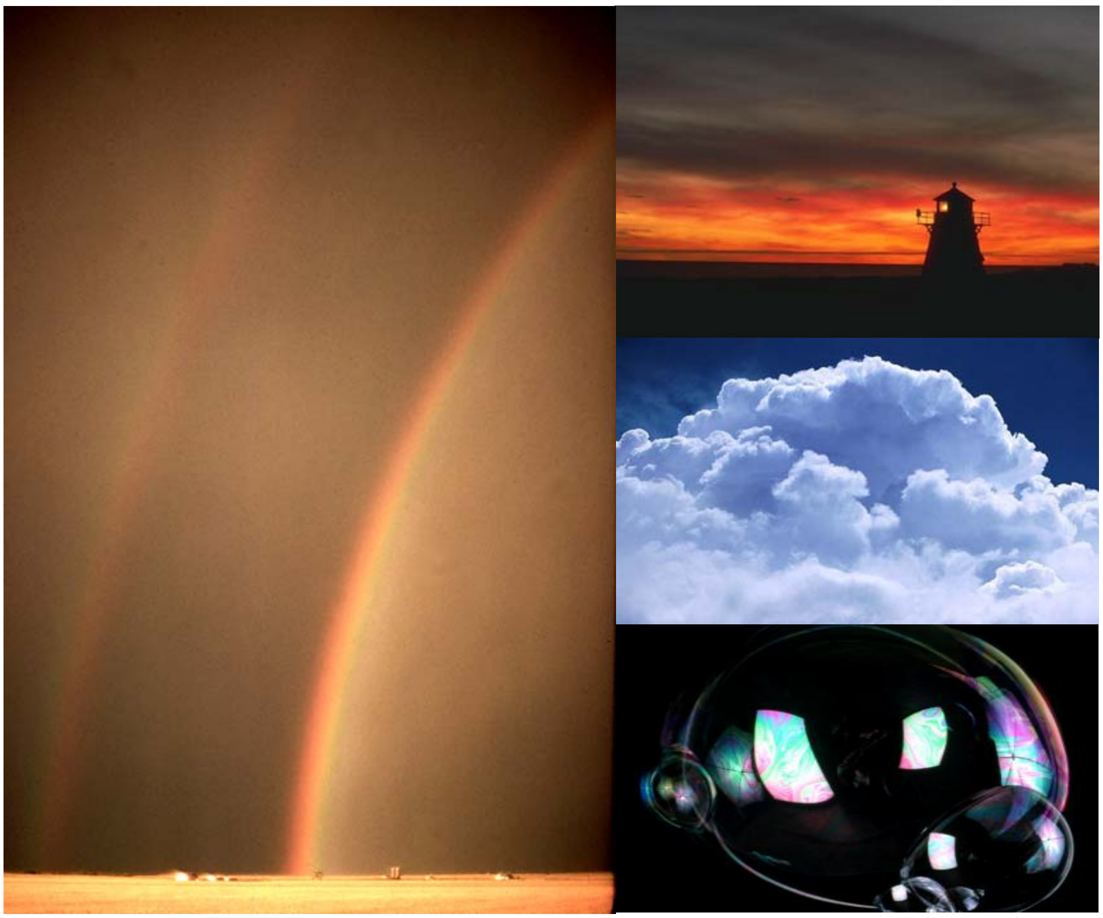
SECTION 1
NON-OBVIOUS CAUSES



This section addresses students' tendency to focus on obvious causes. It introduces students to the concept of non-obvious causes. Non-obvious causes are often overlooked when people generate explanations. Air pressure is typically non-obvious, and historically its effects were attributed to other causes.

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The cause of a *rainbow* can be entirely *non-obvious* to those viewing it. Different colors of light travel at different frequencies. These different frequencies move at different speeds in transparent materials, causing each to refract, or bend, at a different angle. This results in dispersion, or the separation of light into different colors. A rainbow occurs when thousands of tiny water droplets act as prisms, dispersing the light into colors arranged by their frequencies. *(Photo Credit: National Oceanic and Atmospheric Administration/Department of Commerce.)*

What causes a *sunset*? Again, the cause is *non-obvious*. When sunlight travels through the atmosphere to Earth, its rays are scattered by the molecules that make up the air. Higher frequencies of light, such as blue and green, are scattered more than lower frequencies, such as red. When the sun is directly overhead, its light travels the shortest distance possible through the atmosphere to an observer on earth, and not much scattering occurs. But at sunrise and sunset, sunlight travels the longest path through the atmosphere to earth, given the sun's position in the sky, and this causes increased scattering, letting only redder frequencies of light reach earth. Particles in the atmosphere, such as air pollution, smoke, or ash from a volcanic eruption, scatter the sunlight even more, resulting in redder and more dramatic sunsets.

Why does a *soap bubble* reflect the colors that is does and why do the colors change as they do? Again, the cause is *non-obvious*. It has to do with the thickness of the bubble walls, which act as prisms, allowing certain frequencies of light to pass through. As the bubble walls evaporate and get thinner, the colors you see change, eventually turning white as all colors are reflected, and then black as no light is reflected, before the bubble finally pops.

The *shape of cumulus clouds* has a *non-obvious* cause. It is the result of heating and cooling water vapor. As warm air rises, water vapor is brought higher into the atmosphere, where it cools and then sinks within the cloud. It is again warmed as it gets closer to Earth's surface and then rises again. *(Photo Credit: FreeStockPhotos.com, copyright 2002 Daniel Speck.)*

Lesson 1
Air Pressure is Non-obvious but Causes Effects

This lesson draws students' attention to the non-obvious nature of air pressure by having students grapple with the historical puzzle, "Why could pumps only pull water out of mines from a depth of 32 feet or less in the 1500s?"

Understanding Goals

Subject Matter

- Air pressure exists all around us all the time. We sometimes forget to consider air pressure because its effects are such a common aspect of our lives; air pressure becomes non-obvious.

Causality

- When causes or effects are non-obvious, we often have to infer that they exist.

Background Information

The Non-obvious Nature of Air Pressure

Just like fish in water, we are so accustomed to the medium in which we live that we typically fail to notice it. Our bodies continually adapt to the sea of air around us; however, we are usually unaware of these adaptations. They only become obvious when air pressure changes rapidly, such as when we ascend in an airplane and our ears pop. Even in these situations, most people typically seek out obvious explanations before looking for non-obvious ones. This tendency can make sense in everyday life because it uses the most efficient search strategies, but it limits the variables one considers.

Scientifically accepted explanations often involve causes that are hard to notice. You can't observe the causes directly; you have to figure out that they exist. Students need to know that causes can be hard to notice, or even impossible to perceive, so that they don't limit their search for explanations to obvious variables.

Air pressure is a non-obvious variable. It was not formally recognized until 1643 when the mathematician Evangelista Torricelli discovered that air pressure accounted for the height to which water could be pumped out of mineshafts.[1] So it is no surprise that students and laypersons often fail to note air pressure's existence or contribution to an effect. Students have difficulty shifting their focus from the apparent features of tasks to less obvious variables, such as the behavior of air or water.

An Historical Puzzle

This lesson begins by introducing the historical puzzle that led to Torricelli's discovery. In the late 1500's, people tried to understand why pumps could not pull water up out of mines to a height greater than 32 feet. The cause was entirely non-obvious—air pressure. Picture the mine in a sea of air. The weight of the air or the atmospheric pressure pushing on the pool of water at the foot of the mineshafts dictates the height to which the column of water could rise. (For further background information read *The Discovery of Air Pressure: A Brief History* on page 33.) We can't see air pressure. We are so used to it around us that we can't really feel it either. Typically, most people consider primarily obvious causes in their search for a solution. Only when the answer continues to be elusive are less obvious explanations considered. In the lesson, students are asked to generate a list of possible problems that could interfere with removing water from mines. Students typically begin by focusing on obvious variables, such as the tools used or the technology at that time, rather than considering non-obvious variables, such as air pressure, in attempting to explain the water's height.

Note to Teacher: An excellent resource on the history of this problem is the book, *Connections*, by James Burke, particularly pages 72-73.[2]

Inferring the Existence of a Non-obvious Cause

The lesson then goes on to have students construct a type of barometer (although they are not named as such) and to observe what happens inside it. Students notice that the oil stays in the straw at a certain level. Highlighting obvious effects that have no obvious cause can push students to begin to examine non-obvious causes. The lesson uses this strategy to engage students in recognizing the existence of a non-obvious variable—air pressure. After students consider what is going on with the barometers, they go back to the problem of the mines and consider if any connections can be made between the problems in the mines and their barometers. Students should realize that air pressure, a non-obvious variable, is the cause in both situations.

Note to Teacher: This lesson will work best if you do the first two steps, then teach the next lesson, and then come back to the remaining steps. Alternatively, it is possible to teach the lessons in sequence and revisit the ideas from the first lesson in the second one.

Lesson Plan

Materials

- Jar, 16 oz. with straight sides, 1 per pair of students
- Straw, clear plastic, 1 per pair of students
- Gum, 1 stick per pair of students
- Cooking oil, ½ cup per pair of students
- Pipette, 1 per pair of students
- Tape
- Permanent marker, fine tipped, 1 per pair of students
- *Thinking about Hidden or Non-obvious Causes* activity sheet, 1 per student
- *The Discovery of Air Pressure: A Brief History* sheet, 1 per student

Prep Step

- Review the lesson plan, background information, and understanding goals.
- Plan to do this lesson during a week of inclement weather. Students should set up their jars and observe them during a time when the weather changes (sun to rain, hot to cold, calm to windy, etc.). This will cause the liquid levels in the jars to change, which will facilitate the discussion in the second half of the lesson.
- Photocopy the activity sheet, *Thinking about Hidden or Non-obvious Causes* (p. 31).
- Photocopy the sheet, *The Discovery of Air Pressure: A Brief History* (p. 33).

Analyze Thinking

Step 1: Consider the Historical Problem of Pumping Water out of Mines

Pose the following problem, which was encountered by miners in the 1500's:

Miners in the late 1500's faced a problem. Water would flow into the mines when they were excavated to a certain depth, and the miners could not find effective ways to remove the water. Therefore, they would end up abandoning mines that still held silver, iron, salt, alum, and other valuable minerals. A former doctor who was interested in science named Bauer identified the problem as having to do with the depth of the mine shafts. In his writings, he described the most common three methods that were used to remove water, either in combination or separately. The first used cloth balls on a circular chain that soaked up the water at the bottom of the shaft, and were squeezed out at the top of the shaft, and then went back down to collect more water. A second used a giant screw that, as it turned, forced the water upwards. The third used a rotating waterwheel shaft with a crank attached that operated a piston which was partially in the water. It would "suck" water into the cylinder, and then a valve would close at the bottom and open at the top, and as the piston came down the water was forced upwards. The third method worked best of the three but curiously, it could not "lift" water more than 32 feet.

Abandoning productive mines was expensive, but it wasn't until 1630 that the problem was solved.[3]

Review how the miners pumped water out of the mines. Make a drawing on the board to help students visualize the process.

Ask students to work in groups of 3 or 4 and to generate a list of possible problems that might have interfered with pumping water from the mines. Encourage students to draw diagrams or models if it helps them think about the problem.

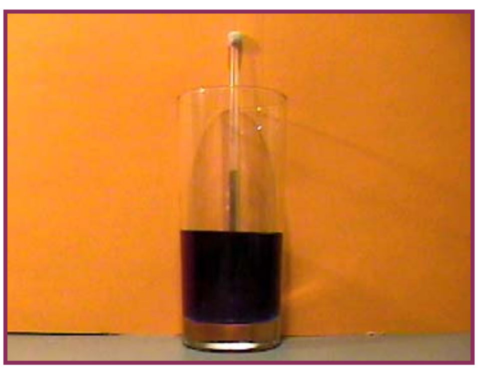
Ask students to share their ideas with the class. Emphasize that all ideas are valuable. Record their ideas on the board.

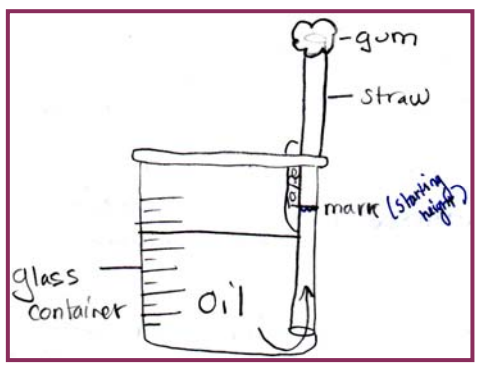
RECAST Thinking

Step 2: Experimenting with the Height of a Liquid in a Tube

Distribute to each pair of students one plastic jar, one straw, one transfer pipette, and one piece of gum. Instruct students to:

- Fill the jar ¼ of the way with cooking oil (about ½ cup), depending upon the diameter of the jar.
- Chew the stick of gum until it is soft. Then use the gum to plug one end of the straw.
- Use the pipette to fill the straw ½ way with cooking oil, then quickly invert the straw into the jar of cooking oil.
- Tape the straw to the inside of the jar. Make sure the straw is at least 1 cm above the bottom of the jar.
- Use a permanent marker to mark the level of the oil on the straw and on the jar.
- Label the jars and set them in an area that does not undergo large fluctuations in temperature.





Step 3: Discussing the Height of a Liquid in a Tube

Ask your students to notice the height of the liquid in the tube. Ask them to consider the behavior of the liquid in the tube.

- Why does the liquid stay in the tube?
- Why doesn't gravity make the liquid fall out of the tube?
- Why does the liquid stay at the level that it does? Can you do anything to get the level to change?

Note to Teacher: Have your students set the jars aside and observe them on a regular basis to see what is happening in the straw and jar. If the students in your class think that the liquid stays in the tube because of a vacuum and/or do not see outside air pressure as the cause of the liquid staying in the tube, then you should observe the height of the liquid in the straw (as in Steps 2 through 4 of the next lesson) and then come back to the rest of this lesson.

Explore Causality

Step 4: Thinking About Hidden or Non-obvious Causes

Introduce the idea that some causes are non-obvious. Ask: "What does it mean for something to be non-obvious?" Collect students' ideas. (*Things you can't see, things that are hard to notice, things that happen over a long period of time, etc*.) Pass out the sheet, *Thinking About Hidden or Non-obvious Causes*. Read and discuss the sheet together. While reading, each student should think of one question they have about the sheet and write it down. It can be a question of clarification, something they don't agree with, something that extends what they read, or a situation where they are unsure if pressure plays a role. Elicit students' questions and discuss them as a class.

Check to see if students can offer some examples of non-obvious causes. Ask, "What are some causes that aren't obvious and what do they cause?" If students aren't able to come up with a good list, offer some examples. For instance:

- A baseball player might have a hidden injury that impacts his or her performance.
- Someone feels a shock after walking across a rug because he or she has a positive or negative charge caused by an excess of protons or electrons—the phenomenon we commonly call static electricity.
- Water droplets form on a window when it is warm inside and cold outside.
- People can float more easily in the ocean than in a pool.

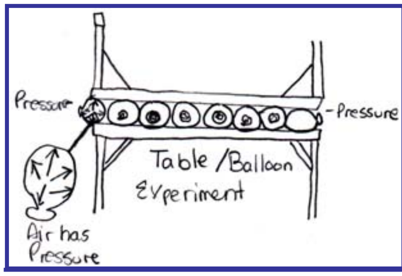
Review, Extend, Apply

Step 5: Connect the Historical Problem and the Liquid in the Tube

Read the passage about pumping water out of mines in the 1500's from Step 1 again. Ask: "How does what you observed with your straws explain what was going on with the pumps in the 1500's?" (*Just as air pressure caused the liquid to rise and fall in the straw, air pressure must be the reason why the pumps could only pull water out of the mines to a depth of 32 feet*).

As a class, read and discuss the sheet, *The Discovery of Air Pressure: A Brief History*. Ask the following questions:

- Do you think the effects of air pressure were obvious to miners in the 1500's? (*No*)
- Are the effects of air pressure obvious today? (*No*)



Lesson 2
When Non-obvious Causes Become Obvious

Non-obvious causes become obvious when certain kinds of changes take place. In the case of air pressure, as the balance of amounts of air pressure changes between two places, corresponding effects make the presence of air pressure more obvious.

Understanding Goals

Subject Matter

- Air pressure exists all around us all the time. We sometimes forget to consider air pressure because its effects are such a common aspect of our lives; air pressure becomes non-obvious.
- Air pressure is the collective result of individual molecules that make up the air bouncing around and applying forces against any object in contact with them.
- A change in air pressure can make its usually non-obvious effects obvious.

Causality

- When causes or effects are non-obvious, we often have to infer that they exist.
- Changes in non-obvious variables that correspond to changes in obvious effects provide evidence that those variables exist and may be responsible for the outcome.

Background Information

Inferring the Existence of Non-obvious Variables Through Obvious Changes in Effects

Sometimes we observe obvious effects that correspond with changes in other variables (even if those variables are typically non-obvious). This can lead us to question whether there are other, as yet undetected, variables that play a role in the outcome. For instance, regular fluctuations in the liquid inside the barometer tube suggest that some variable is responsible. If we find that changes in air pressure correlate with certain outcomes in a predictable way, such as the movement of a liquid in a tube, air pressure may be involved in the movement of the liquid. (It does

NOT mean that there is definitely a causal connection; rather that there is a correlation to be investigated further.)

To introduce the variable of air pressure and to make air pressure around us obvious, in this lesson, students consider the barometers (although they are not named as such) that they created in the last lesson. A barometer is an instrument used by meteorologists to measure changes in atmospheric pressure. These changes are most obvious during times of inclement weather, when weather fronts move into or out of an area. This activity works best if there is a period of fluctuating weather during the time span when students are observing their barometers.

Note to Teacher: This lesson formally introduces the concept of air pressure. It assumes that students already understand that pressure is the force per unit of surface area, where the force is applied perpendicularly to the surface area (Pressure = Force/Area). If they do not, you may want to teach it first. (Activities such as the "bed of nails" where someone, usually the teacher, lies down on a bed of nails, can effectively illustrate the relationship between force, area, and pressure. Students are asked to apply this understanding to air pressure, which is the collective result of the molecules that make up the air applying forces against any surface with which they have contact.)

Lesson Plan

Materials

- Jars that the students set up in Lesson 1
- *Atomic Microscope 3-D* available at www.starkdesign.com or *Virtual Molecular Dynamics Laboratory* available at http://polymer.bu.edu/vmdl/
- Approximately 14 balloons
- 14 one-foot pieces of tubing that fit into the balloons
- Two tables of about the same size

Prep Step

- Review the lesson plan, background information, and understanding goals.

Note to Teacher: Try to do this lesson during a week with variable weather.

Analyze Thinking

Step 1: Considering When We Do Notice Air Pressure

Ask the class the following questions about air pressure:

- Why is air pressure so hard to notice? (*It is hard to notice because it is non-obvious; it is always around us, yet we can't see it, etc*.)
- When are times when we do notice air pressure? (*Usually we only notice it when it causes something that we do not expect, or something that is so obvious that we have to try to figure out what caused it. For instance, when our ears are suddenly hurting and pop, we look for a cause. Often, we fail to notice air pressure until it changes in some way or is no longer there. Since we live in an ocean of air, we are used to air pressure because it's all we have ever known*.)

RECAST Thinking

Step 2: Observing the Height of a Liquid in a Tube Over Time

Over the next several days to a week, have students observe the liquid in the straw that they set up in Lesson 1. Make sure students think about the following:

- Look at where they marked the level of the oil in the straw. What happens to the level of the oil? (*It should fluctuate*.)
- What ideas do they have regarding the fluctuation?

Step 3: Discuss What Students Observe Happening in the Straws

Discuss what students think is going on with the liquid in the straw. Ask: “What do you think is causing the liquid to rise and fall over time?” (*Students might mention obvious causes such as changes in weather or evaporation of the liquid in the jar. They might also mention non-obvious causes such as air pressure.*)

Step 4: Visualizing Air Pressure

If students have not mentioned air pressure, introduce the concept. Ask if they have heard of air pressure. Collect a few ideas. Ask them to draw a model showing what air pressure is and how it works (on individual white boards, in their journals, or on a blank sheet of paper). Give at least 10 minutes for students to think about and develop their models. Encourage students to use the process of model drawing to think through their current assumptions about air pressure. Afterwards, discuss students’ models. Make sure that the following ideas are introduced into the conversation.

- Many individual molecules that make up air are bouncing around.
- Each molecule applies a force perpendicular to the surface that it hits.
- The collective result of all of these bouncing molecules is air pressure. (*The result is pressure, not force because the force is spread over the surface area of the objects the individual molecules hit.*)
- The more molecules bouncing around and the faster they move (*the more kinetic energy*), the greater the air pressure. The fewer the molecules and the slower they move, the lesser the air pressure.
- It can be challenging to visualize air pressure. Pressure is the force per unit of surface area, where the force is applied perpendicularly to the surface area ($\text{Pressure} = {}^{Force}\!/_{Area}$). In order to visualize air pressure, you have to envision numerous bouncing molecules each applying forces against any surface with which they have contact resulting in air pressure.

A good way to help students visualize air pressure as scientists do is to use one of the molecular visualization programs available on the web, for instance, *Atomic Microscope 3-D* available at www.starkdesign.com or *Virtual Molecular Dynamics Laboratory* available at http://polymer.bu.edu/vmdl/.

Step 5: Evidence for Air Pressure: Lifting a Table With Balloons

Say to the students: “The Torricelli experiment and the barometer activity are intended to convince you that air exists (takes up space) and that it exerts pressure. Do you believe it? What evidence can you think of that supports the assertion?” Gather ideas. Then ask: “Is there any evidence that contradicts the assertion?” Gather ideas.

Do the following demonstration:

Place uninflated balloons with tubes to blow into them every foot or so (depending upon the weight of the second table) around the perimeter of a rectangular table. (The tubes are important for safety, to keep the students back far enough from the table, should it fall.) Invert a second table (the smaller table of the two), face down, on the one below, so that the open ends of the tubes are all protruding out from between the tables. Have students volunteer to blow, all at the same time, into each balloon, to see if they can lift the inverted table. Assign students to act as spotters to keep the table from shifting.[4]

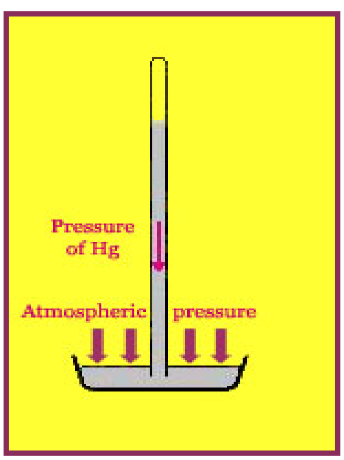
Discuss what happened. Ask, “Does this provide convincing evidence that air exists and that it exerts pressure? Is it convincing to you or not?” Then ask, “Can you think of other ways to demonstrate that air exists (takes up space) and exerts pressure?”

Explore Causality

Step 6: Discuss How Changes in Non-obvious Causes Can Reveal Their Existence

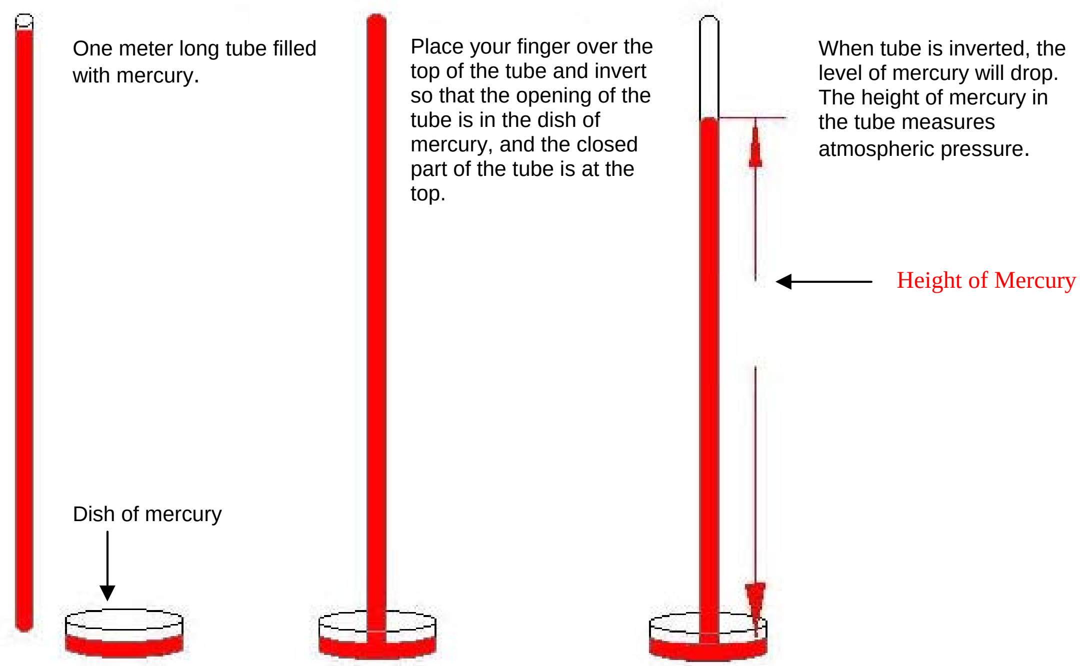
Ask students to consider what the fluctuations in the straw tell them about noticing non-obvious causes. Ask: “When are we likely to notice the effects of air pressure?” (*When the air pressure changes, such as when the weather changes from sunny to rainy. If they observed the jars over a long period of time, they would start to notice that the changes in the liquid corresponded to changes in the weather*.)

Read the following passage to the students:



In 1648, Blaise Pascal confirmed Torricelli's idea of the variability of air pressure. Pascal brought a tube with mercury, like the one Torricelli used (which came to be known as a Torricelli Tube), from sea level to the top of a mountain. Notice that the Torricelli Tube consists of a tube inverted in a dish of mercury. As Pascal went higher up the mountain, there was less air pressure acting on the mercury in the dish (so less mercury was pushed up the tube.) As predicted by Torricelli’s findings about the weight of air pushing down on the mercury in the dish, the mercury in the tube fell with the increase in altitude.

An Example of Torricelli's Tube



Pascal's experiment illustrates how changes in the height of the liquid that correspond with predicted changes in the amount of air pressure helped convince people that air pressure exists. Ask your students:

- What does this story tell you about non-obvious variables in general? (*It suggests that it is easier to detect non-obvious variables when there are changes in the variable that correspond with obvious changes in the effect.*)

Review, Extend, Apply

Step 7: Reasoning About a Change in Air Pressure in Everyday Contexts

Ask your students to think about instances when air pressure changes, and there is also a corresponding change in the outcome that fluctuates with the change in pressure to suggest that the two may be linked. Examples include the following:

- You notice your bike's tires look a little low, but after you ride the bike, they appear full.
- You go to a party store to pick up balloons. On the ride home, in cold temperatures, the balloons seem to deflate a little. But once inside the house the balloons seem full again.

- You find a football during the winter in the garage that is partially deflated. Last summer, however, it was fully inflated.
- Your water bottle has a regular shape on the top of a mountain, but when you hike into the valley, it looks crushed. When you return to the top of the mountain, it looks normal again.

Note to Teacher: Some of these examples will be understood better after students learn about Boyle's and Charles' Law. You may wish to revisit this brainstorm after teaching Section 3.

Discuss how we might not notice the effects of air pressure until the effects are troublesome. Give examples of altitude sickness or divers getting the bends. In both cases, the non-obvious effects of air pressure become obvious because your body reacts to a pressure change, making it obvious. (*You get light-headed, disoriented, etc*.) The result is that your body's pressure changes to try to maintain balance or equilibrium with the outside pressure, resulting in effects that can be very dangerous.

Resources for Section 1

Lesson 1

Thinking About Hidden or Non-obvious Causes Sheet

The Discovery of Air Pressure: A Brief History Sheet

Lesson 2

No Additional Resources

Thinking About Hidden or Non-obvious Causes

Air, and therefore air pressure, exists all around us. Air pressure and changes in air pressure cause many things to happen. Most of these things we don't notice because:

- There may be no changes to notice. Air pressure often causes things to be the way that they are. If all of the air pressure suddenly disappeared, you WOULD notice it.
- Changes in air pressure are usually small enough that we don't notice them until something surprising happens, like our ears suddenly popping when we drive up a mountain or fly in an airplane. Even then, we usually look first for causes that we can see or that have to do with our ears, not causes that we can't see.

Finding Hidden or Non-obvious Causes

Most people look for obvious causes first when something happens. For example:

> A mother with a baby is in a plane. Before and during take off, the baby is happy. About 10 minutes into the flight, the baby becomes increasingly fussy and then starts to cry. The mother wonders why he is crying and looks to see if his diaper is wet, if he is hungry, and then as he cries in pain, whether a zipper is pinching his skin. Then as her own ears start to hurt, she begins to consider other, hidden causes of the baby's crying. Because her ears hurt AND the baby is crying, she can figure out that it probably isn't something just in her ears. The mother reasons that her baby's ears hurt as well, which would then lead her to look for a non-obvious cause that affects both of them, and that would necessarily lie outside of them. Otherwise, she would probably check her ears before thinking about what is around them that she can't see.

Notice how the mother first looks for obvious causes and local causes. Obvious means "right in front of" or "easily discovered or understood." Local, in this case, means "closest to the effect." So if the pain were in her ear, she would usually check there first instead of checking for changes in her environment.

Analyzing Hidden or Non-obvious Causes

When scientists think about possible causes, they consider obvious and non-obvious possibilities. When you are trying to determine the cause of an event:

1. Ask yourself: What are some possible causes? List these out on a piece of paper.
2. Now look at your list. Which ones are local (closest to the effect)? Do you have any that are non-local (far from the effect)? If not, try to think of some.
3. Which ones are obvious (right in front of you or easily discovered/understood)? Do you have any that are non-obvious (not right in front of you or not easily discovered/understood)? If not, try to think of some possible non-obvious causes.
4. Are there other possibilities that you can think of? If so, add them. If not, go over your list again and think deeply about which cause best fits the evidence.

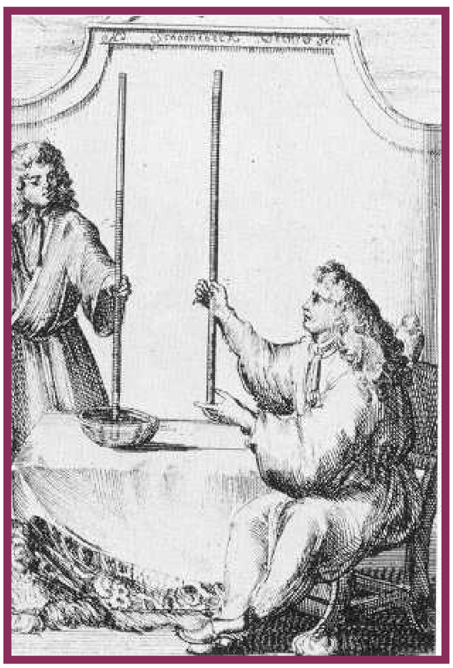
Considering obvious and non-obvious possibilities can help you create better explanations in science.

The Discovery of Air Pressure:
A Brief History *

The Problem: Pumping Water out of Mines

The problem of pumping water out of mines was both puzzling and expensive. It was mysterious that water could not be pumped higher than 32 feet. In trying to explain what was going on, people focused on obvious variables such as imperfections in the pumps themselves or fluid that seeped in from outside the pump. Non-obvious variables, such as air pressure, were not considered as an explanation for the puzzle.

Moving Toward a Solution: Torricelli's Experiment



In 1643 Evangelista Torricelli, a mathematician who had studied with Galileo, became convinced that the weight of the air pushing on the pool of water at the foot of the mineshafts had something to do with the height to which water would rise. He designed and had his assistant, Vincenzo Viviani, carry out an experiment to test the idea. Viviani took a 6 foot long glass tube and filled it with mercury. Then he placed his finger over the opening and inverted the tube into a bowl of mercury with the sealed end up, and measured the resulting height of the mercury column.

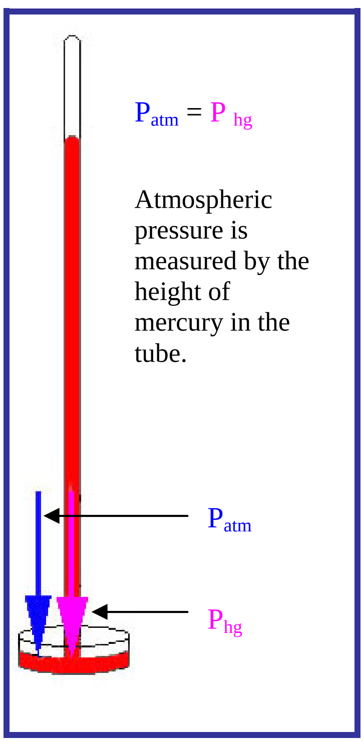
(Mercury, with a density of 13.6 g/ml., is much denser than water. Torricelli realized that if he used mercury he would not have to use such a long tube. If he used water, he would have needed a column of water 13.6 times that of mercury, or about 32 to 33 feet high. Recognize that number? Of course, today we know that working with mercury has some serious health risks!)

*This information was adapted from Burke, J. (1978). *Connections*. Boston: Little, Brown & Company.

The mercury fell instead of remaining at the top, and an empty space, or vacuum, was created at the top of the tube. (At the time, scientists thought that a vacuum was impossible. Galileo believed that no such thing existed; however, some of Torricelli's friends had been secretly experimenting to see if one could be created.)

Torricelli observed that the column of mercury rose and fell in a manner that corresponded to the weather. On clear days, the column would be relatively high, but before and during a storm, it would drop. He realized that the height of the mercury column must be in some way connected with the atmosphere.

Measuring Air Pressure



Torricelli reasoned that the weight of the column of mercury was equal to the weight of the air column pushing down on the bowl of mercury. If the weight of either one changed, then the height of the column of mercury should also change.

Torricelli's findings spurred many new discoveries, such as the behavior of gases, the existence of oxygen and so forth. It also led to technological innovations such as jet engines and hot air balloons.

Making Connections: How does Torricelli's Tube explain why pumps could not pull water out of mines from a depth greater than 32 feet?

Reinforcement Activities

Going to Great Heights (p. 36)—This activity enables students to see for themselves that water will not rise higher than approximately 32 ft. It is a reconstruction of the historical puzzle that led to the discovery of air pressure and its role in pumps and siphons.

Reasoning About Non-obvious Causes (p. 37)—This activity sheet asks students to analyze obvious and non-obvious causes in everyday examples that are not air pressure-related. It reinforces the concepts in the lessons in everyday contexts.

Is Air Pressure Involved? (p. 39)—This activity provides a list of situations that may involve air pressure in some way as a non-obvious cause of an outcome. Students are asked to consider if and how air pressure might be involved, and to revisit the list throughout the unit as they learn more about how to answer the questions. A teacher resource sheet that explains the role of air pressure in each situation follows.

Going to Great Heights
(Reinforcement Activity)

This activity lets students see for themselves that water will not rise higher than approximately 32 ft. It is a reconstruction of the historical puzzle that led to the discovery of air pressure and its role in pumps and siphons.

Materials

- 40 feet of transparent plastic tubing
- One gallon jug of water
- A bucket or tub filled with water
- Access to a building that is taller than 40 feet high.

Steps

- Take 40 feet of transparent plastic tubing and a gallon of water, and go to the roof of the building (or to a window that is higher up than 40 feet.)
- Let the tubing down the side of the building and have somebody put the lower tip of the tubing inside a bucket sitting on the ground that is filled with water.
- Pour water from the jug into the top of the tubing. Lots of bubbles will be observed in the tub, but will the water spill out? (*The water you pour from above stays inside the tubing instead of flowing out.*) Can you fill the whole 40 feet of tubing with water? What happens?

Follow-up Questions for Class Discussion

Explain to your students why barometer readings on TV weather reports are always given as 30 inches or thereabouts. Ask: “Does the height to which you could fill the tubing (about 32 to 33 feet) and the 30-inch readings have anything to do with each other?” (*Yes, they are related. Air pressure acts on water in a tube in a similar way that it acts on a tube of mercury. If you put them side by side, they would rise and fall in a similar fashion as the air pressure changes. It’s much easier, however, for scientists to use mercury rather than water. Since mercury (13.6 g/ml) is much denser than water (1 g/ml), the tube of water would need to be 13.6 times the tube of mercury for the same results, or about 32 to 33 feet*.)

Reasoning About Non-obvious Causes

(Reinforcement Activity)

The activity sheet *Reasoning About Non-obvious Causes* asks students to analyze obvious and non-obvious causes. It serves to reinforce the concepts in the lesson and in everyday contexts. As you review the worksheet with your students, assess whether they make connections to previous lessons on air pressure.

Hand out the activity sheet, *Reasoning About Non-obvious Causes*. After students complete the activity sheet, consider the following:

- What do students consider to be possible obvious and non-obvious causes?
- Do students make connections to previous lessons on air pressure? If not, review how air pressure often acts with non-obvious effects. It is important to consider air pressure when thinking about phenomena. This is not to say that air pressure will *always* play a role; only that it *might* play a role.

Reasoning About Non-obvious Causes
(Reinforcement Activity)

Name ______________________________ Date ________

Below are some quotes from younger students. Underline places where students are reasoning about obvious causes, and circle places where they are reasoning about non-obvious causes. *Keep in mind that students may not be using the correct scientific reasons for what they think is happening!*

Stephanie, Katie, Robbie and Ryan are examining Robbie's bike that has several big areas of rust on it:

- *Robbie*: I don't know where this rust came from. Maybe it's because I left my bike outside on the grass overnight and the dew made it rust?
- *Katie*: I don't agree. You never should have taken your bike to the beach with you. That salty air rusted your bike for sure.
- *Stephanie*: I was thinking that it might be because you wrecked your bike a few months back. Maybe those are areas where the paint chipped off.
- *Ryan*: Maybe your bike has a disease or something.

Trevor and Jared are walking in the woods. They notice that a big tree has fallen and is beginning to decay.

- *Trevor*: Wow! Look at that tree. It's huge. Look, it's all rotten.
- *Jared*: Hey, there's a sow bug. Bugs must be making it decay.
- *Trevor*: Yeah, and probably worms, too.
- *Jared*: I see a mushroom growing on it. There's probably fungi inside it too.
- *Trevor*: We learned in science that microbes help to break things down. You can't see them without a microscope, though.

Is Air Pressure Involved?
(Reinforcement Activity)

1. An inventor who likes to snorkel decides to invent a snorkel that unrolls like a garden hose so that he can swim in deeper water and see more fish. Before he tests it out, a friend convinces him that the new snorkel is not safe. What argument did she make to convince him?
2. Why do your ears pop when taking off in a plane?
3. Why do some people put their tennis balls in the freezer?
4. A hurricane is approaching. Meteorologists advise people to open their windows. After the storm passes, people who did not open their windows notice that their windows are broken and have fallen outside their houses as though they have blown out. What is going on?
5. A Social Studies teacher is telling a story in the teacher's lounge. "It was a hot day and I bought a set of helium balloons for a party. I put them in the far corner of the car so that they were away from the open window. The balloons stayed there while I was in the parking lot, but as soon as I got on the highway, they made a beeline for the open window and floated out. How did the balloons know how to find the only open window?" What did the science teacher say to him?
6. Ian is pumping air into the tires on his bike. The tires are pretty flat and at first it is easy to push the pump up and down to fill the tires. The more full the tires become, however, the harder it is to move the pump. Eventually, it gets so hard that Ian gives up. "Good enough" he decides. Why did it get increasingly difficult to push the pump up and down?
7. Some of the earliest tires were made of metal in order to support the weight of the vehicle. Today tires are made of rubber. How can rubber support the weight of a vehicle? An average car weighs about 3000 lbs.
8. Tamika brought her water bottle, which was half full of water, on the plane with her when going to visit relatives. About an hour into the flight, she tipped the bottle upside down to drink from it and pulled the top open with her lips. As soon as she did, the water spurted out down her throat and left her coughing. What happened?

Is Air Pressure Involved?

Teacher Resource

Note to Teacher: The following explanations are meant to guide you in your own understanding. Don't share the explanations with your students yet.

1. **An inventor who likes to snorkel decides to invent a snorkel that unrolls like a garden hose so that he can swim in deeper water and see more fish. Before testing it out, a friend convinced him that the new snorkel is not safe. What argument did she make to convince him?**[5]

   She told him to think about the effects of the air pressure inside his lungs and the air pressure of the outside air. If he is under the water, there will be a lot of pressure on his body, and thus the air in his lungs will be higher pressure than the outside air. When he puts the long snorkel in his mouth, the pressure of the air in his lungs will even out with the air outside and his lungs might collapse.

2. **Why do your ears pop when taking off in a plane?**

   As an airplane takes off and lands, there are great changes in altitude. Our bodies sense this pressure change through our ears. As you take off in an airplane, the pressure in your ears (as in the rest of your body) must adjust to the change in altitude. You can sense this change when your ears pop.

3. **Why do some people put their tennis balls in the freezer?**[6]

   Tennis balls have a higher internal pressure than the outside air pressure. To maintain that higher internal pressure, people sometimes put their tennis balls into the freezer, since the lower temperature cools the ball, decreasing the internal pressure in the ball so less air leaks out.

4. **A hurricane is approaching. Meteorologists advise people to open their windows. After the storm passes, people who did not open their windows notice that their windows are broken and have fallen outside their houses as though they have blown out. What is going on?**

   During a hurricane, the atmospheric pressure drops. If the house is closed up, the inside pressure will remain at the level that it was at before the storm. Therefore, the relative air pressure outside the house ends up being less than the air pressure inside the house. Unless the windows are opened so that inside and outside air pressures can equalize, if the differential is big enough, the greater pressure inside the house will push the windows out, because there is not enough pressure from the outside to push back in the opposite direction.

5. **A Social Studies teacher is telling a story in the teacher's lounge. "It was a hot day and I bought a set of helium balloons for a party. I put them in the far corner of the car so that they were away from the open window. The balloons stayed there while I was in the parking lot, but as soon as I got on the highway,**

they made a beeline for the open window and floated out. How did the balloons know how to find the only open window?" What did the science teacher say to him?

The science teacher told him that the balloons didn't actively know or do anything. They were pushed out of the window by the air pressure in his car. When he got on the highway, the air outside his car was moving faster than the air inside of his car. According to Bernoulli's principle, the pressure in a fluid (such as air) decreases as the speed of the fluid increases. Therefore, the air pressure outside the car was lower than the air pressure inside the car. The balloons were pushed from an area of higher pressure to an area of lower pressure.

6. **Ian is pumping air into the tires on his bike. The tires are pretty flat and at first it is easy to push the pump up and down to fill the tires. The more full the tires become, however, the harder it is to move the pump. Eventually, it gets so hard that Ian gives up. "Good enough" he decides. Why did it get increasingly difficult to push the pump up and down?**

   When the tires were deflated, there was relatively low air pressure inside. As Ian added air to the contained space, the air pressure increased. As the air pressure increased, it pushed back on the pump with increasing pressure as Ian forced more air into the fixed space in the tire.

7. **Some of the earliest tires were made of metal in order to support the weight of the vehicle. Today tires are made of rubber. How can rubber support the weight of a vehicle? An average car weighs about 3000 lbs.**

   The weight of the car is supported by the air pressure in the tires, rather than by the rubber that the tires are made of. The molecules that make up the air in the tire are bouncing all around inside the tire, and the collective result of the force that they create results in the air pressure that supports the car.

8. **Tamika brought her water bottle, which was half full of water, on the plane with her when going to visit relatives. About an hour into the flight, she tipped the bottle upside down to drink from it and pulled the top open with her lips. As soon as she did, the water spurted out down her throat and left her coughing. What happened?**

   When Tamika closed her bottle before the flight, the air pressure in her bottle was the same as the air pressure at ground level. When the plane took off, the air pressure inside the plane decreased, because there is less air pressure at higher altitudes than at lower altitudes. Even though the passenger cabin is pressurized to minimize discomfort, its pressure is still lower than the pressure at ground level. The water in the bottle was pushed from an area of higher pressure to an area of lower pressure (Tamika's mouth).

Endnotes for Section 1

[1] Burke, J. (1978). *Connections*. Boston: Little, Brown & Company.

[2] Burke, J. (1978).

[3] Burke, J. (1978).

[4] Liem, T. (1981). *Invitations to Science Inquiry*. Chino Hills, CA: Science Inquiry Enterprises.

[5] Adapted from Jewett, J. W. (1996). *Physics Begins With Another M…Mysteries, Magic, Myth, and Modern Physics*. Boston: Allyn and Bacon.

[6] Adapted from Jewett, J. W. (1996).

SECTION 2
PASSIVE CAUSES



This section addresses students' tendency to think of pressure as a force that actively pushes and is unidirectional. Students are encouraged to think about pressure as a passive cause that is omnidirectional.

Section 2
Table of Contents

Explanation of Photos on Preceding Page

What makes an *arch bridge* stay up? It can be described as a form of *passive causality*. The distribution of weight and the balance of forces results in the bridge staying up. We don't notice anything actively happening to keep the bridge up, but if the balance was disturbed, we would quickly realize how it caused the bridge to stand.

An *umbrella* works *passively* to perform its function. It simply acts as a barrier to keep the rain, snow, or sun off of the person holding it. While it doesn't behave actively to do anything—it just exists—removing it on a rainy day leads to a clear and immediate reminder of what it was doing (and to a wet head!)

Solar panels convert the sun's rays into electricity. At the level at which most people analyze what is going on, the panels act *passively* to perform their function. Other methods of generating electricity require work: consider a hydroelectric dam, which relies on the power of moving water. Solar panels produce electricity directly from light energy. We don't notice anything happening to produce this electricity, until a cloudy day interrupts the solar panel's function.

Lesson 3
Passive Causal Agents and the Omnidirectional Nature of Air Pressure

This lesson draws students' attention to passive causal agents, such as air pressure, in a system. Students are encouraged to conceptualize air pressure as passive and omnidirectional, with molecules that make up the air bouncing off of the surfaces with which they have contact in all directions equally.

Understanding Goals

Subject Matter

- Air pressure exists all around us.
- While individual molecules that make up the air bounce all around and push as they collide into things, the collective result, air pressure, is passive. Air pressure doesn't actively push on things, it just exists around them, forming a boundary in an omnidirectional sense. A common mistake is to think of air pressure as an active force pushing down in one place and in one direction (usually down).

Causality

- Some causal agents behave passively to result in effects.
- It can be difficult to notice passive causes. Causal agents that are perceived as "active" are more likely to be recognized.
- Being unaware of passive causes can limit the scope of variables that we consider as possible explanations for events around us.

Background Information

Passive Versus Active Causal Agents

When we envision causality, most of us picture some type of action leading to some type of effect. In this image, the cause is seen as active—it does something to lead to a result. However, some forms of causality do not neatly fit this image. Instead, they bring about outcomes (sometimes obvious and sometimes not) in ways that one might call passive. What do we mean by this? Here is an example:

When riding in a car at fifty miles per hour, everything in the vehicle is moving at 50 miles per hour, including us. The car has brakes to stop it. What stops us? Well, as long as the stopping of the car is gradual, we might not notice the role that our seatbelt plays in helping to stop us. It is a passive restraint system. When a car stops short (amplifying the effect), we are more likely to recognize our seatbelt as the cause that holds us in our seats each time the car stops. A more active causal agent would have a greater chance of being recognized. For instance, if a hand came out of the dashboard and pushed passengers into their seats each time the car came to a stop, students would certainly recognize the hand as a causal factor in the system.

Unidirectionality Versus Omnidirectionality

In order to understand air pressure as scientists do, students need to think about air pressure as something that exists all around them and works in an omnidirectional manner. However, as soon as we begin to use language like "push," students begin to associate this with a force. This notion is very appealing because it portrays the air pressure as "doing something." It is seen as an active causal agent. This typically leads students to the idea of air pressure pushing down in a unidirectional manner. Confusing the matter further, we do speak of individual molecules that make up the air as forceful—bumping into and bouncing off of things. Air pressure is due to the collective effect of individual molecules colliding and bouncing around. It is well documented that students have difficulty reasoning about collective behaviors and moving back and forth between levels of individual interaction and collective, emergent outcomes.[1] A further type of confusion may arise, in that some students think of the molecules that make up the air as passive, but visualize pressure as a distinct and active agent that is separate from the molecules, and pushes them along. These students do not envision the molecules bouncing off of the objects in the system.

Beliefs About Gravity and Density Can Inadvertently Reinforce a Unidirectional View

Understanding air pressure as omnidirectional is especially hard when students understand some things about gravity and density. The earth's gravity holds the molecules of the atmosphere close to Earth. The molecules are most dense closest to the earth's surface, and least dense at higher altitudes. When students try to integrate these ideas with concepts of air pressure, it results in the belief that air pressure just pushes down because gravity is pulling molecules that make up the air towards the earth's surface. However, this view leaves out part of the story of the atmosphere. The particles are energized by sunlight and are bouncing all around.[2] Therefore, pressure acts omnidirectionally instead of unidirectionally. It does follow from the logic above that there are different amounts of pressure at different altitudes, although this doesn't mean that pressure only pushes down.

Lesson Plan

Materials

- Balloon, 1 per class
- Orange juice can, 1 per class

Prep Step

- Review the lesson plan, background information, and understanding goals.
- Remove the bottom from the orange juice can.

Analyze Thinking

Step 1: Gathering Current Ideas

Set a book on the table at the front of the class. Ask: "How does air pressure affect this book? Take a moment and write your ideas on a piece of paper or draw a model."

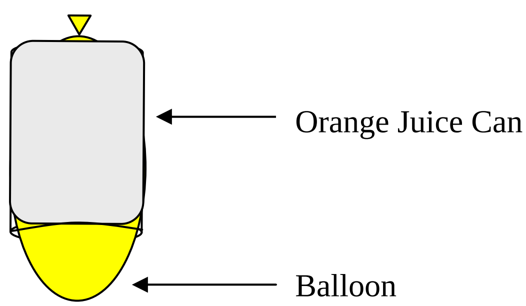
Note to Teacher: Walk around and observe the students as they write their ideas and draw their models. In particular, note models that show a "pushing down" theory of air pressure. Have these models available for the RECAST activity below.

Have several students share their ideas with the class verbally or put their models on the board.

RECAST Thinking

Step 2: Making Predictions About the Effects of Air Pressure

Present the balloon and the orange juice can. Blow up the balloon into the orange juice can until it extends out the bottom of the can.



Have students predict what air pressure will do to the balloon when you turn the can over. (*Responses might include that nothing will happen, or that air pressure pushes downward on the balloon, squishing it down.*)

Step 3: Considering Evidence for the Omnidirectional Behavior of Air Pressure

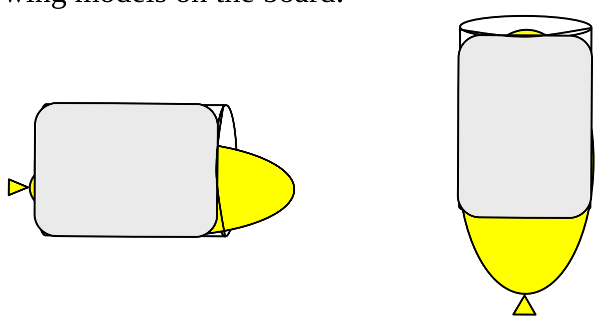
After you have collected students' predictions, slowly turn the can upside down and have students observe what happens. (*Nothing happens.*)

Have students consider why this is a problem for the "pushing down only" theory of air pressure. Ask: "If air pressure only pushed downward on objects, what would have happened to the balloon?" (*The balloon would have shifted and squished out the other end of the can.*)

Explore Causality

Step 4: Considering Which Model Best Explains the Evidence

Discuss unidirectional versus omnidirectional causality with your students. Put the following models on the board:



Ask students:

- Is this what the balloon and can looked like? (*No, the balloon kept its shape.*)
- If these diagrams illustrate what the balloon should have looked like if pressure only existed in a downward direction, and the balloon didn't look like this, what can you conclude from this activity? (*The unidirectional model did not explain what happened.*)
- Do the results support any other model? *(Yes, an omnidirectional model that says air pressure exists in all directions equally.)*

Relate what students observe to the idea of passive causes. Explain that the unidirectional model fits with our expectations about causes, that they *actively* do something. In the unidirectional model, the cause is a force that is pushing down on the balloon. We expect to see a change in a cause and effect relationship. However, causes don't always work that way. Sometimes there is no observable change. Causes don't appear to be "doing" anything, even though they may be maintaining the status quo. Air pressure is passive in this way. It pushes in all directions at once (is omnidirectional) so unless we unbalance it in some way, we may not realize that it is doing anything.

In Section 1, students lifted a table using balloons. Remind students about this activity. What does the outcome suggest for the unidirectionality or omnidirectionality of air pressure? If air pressure only pushed downward, could the air in the balloons push the table upwards?

Review, Extend, Apply

Step 5: Revisiting Students' Earlier Models

Have students go back to the models they drew in Step 1. Ask:

- Based on what you learned in class today, did you model unidirectional or omnidirectional causality in your drawing of the book on the table?
- What should a model of air pressure look like with a book on a table? (*The model should show the book on the table with pressure existing around the book in all directions equally*.)

Lesson 4
Considering How Well Models Depict Air Pressure as Omnidirectional

This lesson asks students to consider some different models of air pressure. By contrasting models that depict air pressure using arrows versus dots, students consider which model better illustrates the omnidirectional, passive nature of air pressure.

Understanding Goals

Subject Matter

- ❖ Arrows are often used to depict air pressure in illustrations and models.
- ❖ Force and pressure are two related, yet distinct concepts. People tend to confuse the two. Models that use arrows can fuel this confusion.
- ❖ We can choose to use other models and/or to be aware of how models with arrows can reinforce confusion between force and pressure.

Causality

- ❖ If a passive causal agent is perceived as "active," it is more likely to be recognized.
- ❖ Being unaware of non-obvious or passive causes limits the scope of variables one considers when generating explanations for given events.

Background Information

Air Pressure as Omnidirectional Rather Than Unidirectional

In order to understand air pressure as scientists do, students need to think about air pressure as something that exists all around them and behaves in an omnidirectional manner. However, the language and models that we use can inadvertently reinforce a unidirectional model. People often use the terms "force" and "pressure" interchangeably, even though they represent two different things. Air pressure is a scalar quantity. In physics, this means that it can be specified by its magnitude or size without paying any attention to direction. On the other hand, force is a directional quantity. In order to describe it completely, you need to specify both its magnitude and its direction.

Explain that part of the problem that students have in visualizing air pressure, which leads them to see it as forceful (having a direction), has to do with thinking about the individual molecules that make up the air versus the effect of all the molecules together. While each individual molecule DOES have a force and therefore a direction, air pressure is all of them together bouncing around, which results in omnidirectional pushing, not a push in a certain direction.

Models That Reinforce Erroneous, Force-like Conceptions

Students (and many textbooks) often use arrows to represent air pressure in models that they draw. If students depict a book on a table, their models typically show arrows pointing downward towards the book. They think of air pressure "pushing down" on the book, like a force, rather than envisioning the individual molecules colliding and bouncing off the book in all directions equally—a collective behavior which results in air pressure. If students depict a balloon in the air, their models typically show arrows pointing towards the balloon in all directions. Although more accurate than a unidirectional model, this model still shows that students think of air pressure actively pushing in on objects, like a force, rather than air pressure as existing in a passive sense.

In this lesson, students compare models depicting air pressure, and determine which model best conveys the omnidirectional and passive nature of air pressure.

Lesson Plan

Materials

- Inflated balloon, 1 per class

Prep Step

- Review the lesson plan, background information, and understanding goals.

Analyze Thinking

Step 1: Gathering Current Models

Present an inflated balloon to the class.

Ask: “How does air pressure work to give a balloon its shape and size? Think about this for a moment and then draw your ideas on paper.”

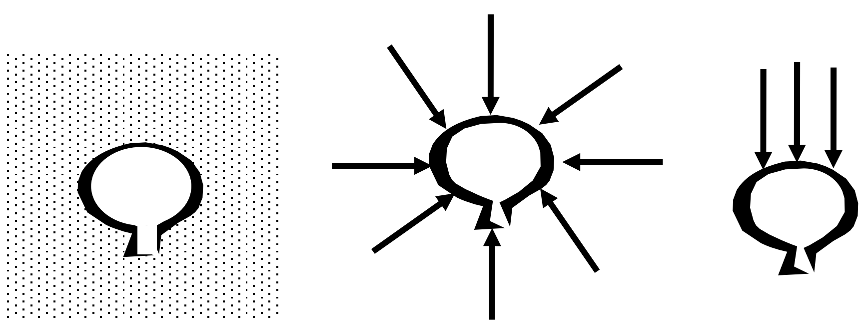
Ask several students to share their drawings with the class. (Try to get a variety of models on the board—unidirectional models, omnidirectional models with arrows, etc.)

Note to Teacher: Presumably students will use arrows to depict air pressure in their models. Do not address this issue yet.

RECAST Thinking

Step 2: Considering What Different Models Emphasize

Put the following air pressure models on the board if they are not already represented in students’ models:



Model A Model B Model C

Note to Teacher: The models above are not relational because they do not show the air pressure inside of the balloon compared to the air pressure outside of the balloon. For now, focus on what is happening outside the balloon with the dots versus arrows models of air pressure, so that the students understand the distinction between them. Introducing students to relational causality is the focus of Section 3.

Ask: "Which model do you think does the best job showing how the balloon gets its shape?"

Discuss their ideas. Encourage students to critique each model and to consider what shape the balloon would have in each instance. Models A and B would both work (except for the lack of pressure on the inside which will come up in later lessons).

Ask: "What would happen in the case of Model C?"

Have students discuss what shape the balloon would have in Model C. If a student does bring up the lack of air pressure pushing out, underscore that there IS pressure pushing out, and this will be discussed in later lessons. An even better set of models WOULD show both inside and outside air pressure.

Explore Causality

Step 3: Considering What Causal Assumptions Are Illustrated by Each Model

Discuss the causality represented in the models with students. Ask:

- "Which model (or models) represents air pressure using unidirectional causality?" (*Model C.*)
- "Which model (or models) represents air pressure using omnidirectional causality?" (*Models A and B.*)
- "Of the two, which model do you think more accurately represents air pressure?" (*The students might side with either Model A or B at this time.*)

Ask students to think about the terms *force* and *air pressure* and what they mean. Have several students share their definitions with the class. If it has not already been mentioned, clarify for students the difference between force and air pressure. (*A force is a push or pull on an object. Air pressure is the collective result of air particles applying forces against any object in contact with them.*)

Ask:

- "Which of the two models represents force?" (*Model B, with the arrows acting on the balloon in all directions.*)
- "Which of the two models represents air pressure?" (*Model A, with the dots.*)

Discuss the difference between force and air pressure. Note how people often use the terms “force” and “pressure” interchangeably, even in models, though they represent two different things. Emphasize that air pressure is a scalar quantity. In physics, this means that it can be specified by its magnitude or size without paying any attention to direction. In other words, it’s just an amount. On the other hand, force is a directional quantity. In order to describe it completely, you need to specify its magnitude and its direction.

Ask the students to recall what they learned in Lesson 3 about passive causes. Explain that air pressure is a passive cause in the sense that it exists, but doesn’t actively push in any one direction. Instead, it acts in all directions. We often don’t notice air pressure unless it changes. Ask,

> “Do you think an arrow model or a dot model is a better depiction of the passive nature of air pressure?” (*The dot model.*) “Why?” (*The arrows give air pressure a sense of activeness, as though it is pushing on the balloon, while the dots do not seem as active, they’re just there.*)

Remind students that people have difficulty reasoning about passive causes. It is very easy to fall into the pattern of reasoning about air pressure as active, and using models that make air pressure look active entices us to do so. This can lead to scientifically incorrect ideas.

Add, as a caveat to this discussion, that when air pressure changes or is unbalanced, it can cause dramatic effects in an active sense. They will have the opportunity to learn about this in later lessons. But when air pressure is balanced, its effects typically go unnoticed.

Review, Extend, Apply

Step 4: Revisiting Students’ Earlier Models

Have students return to their own models of the inflated balloon that they drew at the beginning of the class. Ask: “Was air pressure well-represented in your model? If not, revise your model.”

Suggest that students use dots to represent air pressure for the remainder of the unit.

Resources for Section 2

No Additional Resources

Reinforcement Activities

Water in a Straw (p. 57)—Many students know that if you put your finger over the top of a straw while it is in a fluid, you can pick the straw up and the fluid will remain in the straw. This activity helps students make the connection between this phenomenon and what they have learned about the omnidirectional nature of pressure.

Water in a Cup (p. 59)—In this activity, students apply what they have learned to a counter-intuitive phenomenon: that water turned upside down in a cup with a card across the cup stays in the cup! This activity reinforces the concept that air pressure acts omnidirectionally.

Why Does the Top Fly Off of the Teapot? (p. 61)—Students are asked to reason about what is happening when air is blown into a plastic teapot, resulting in the top flying off. Many people think that air pressure pushes down. If this were true, how can the lid pop up? This activity reinforces the concept that pressure acts omnidirectionally and that increasing the pressure inside the teapot causes the lid to pop off.

The Squished Cup: Is Water Pressure Unidirectional or Omnidirectional? (p. 62)—Students are shown a picture of a Styrofoam cup and a picture of a similar cup that was brought to a depth of 1770 ft. underwater. They are asked to consider what the evidence suggests about the nature of water pressure as an analogy to air pressure.

Water in a Straw
(Reinforcement Activity)

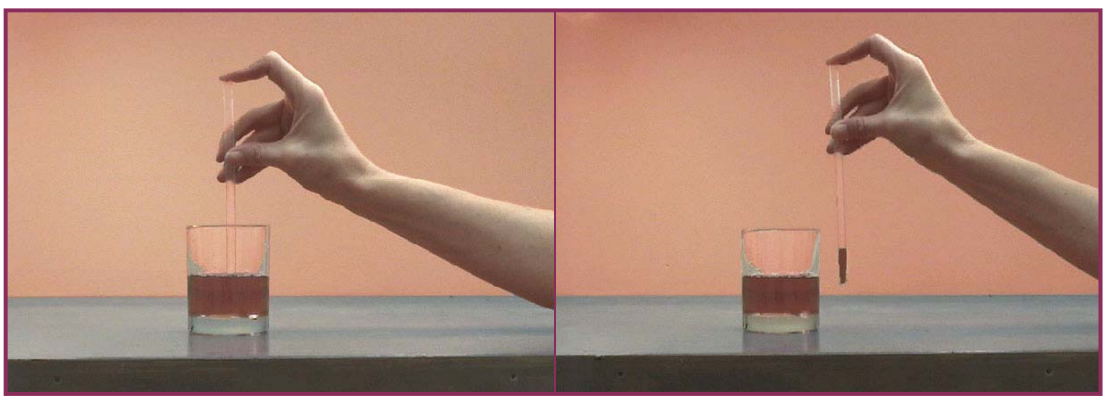
In this activity, students experiment with water in a straw by placing a finger over the top of a straw and taking the straw out of the cup. Students consider what this activity suggests about the nature of air pressure.

Materials

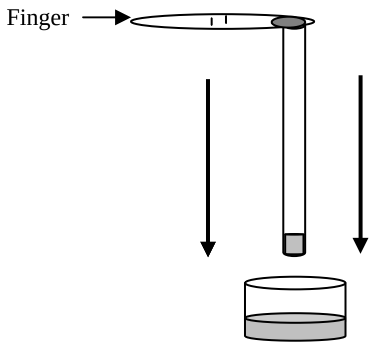
- Straw, 1 per student
- Cup of water, 1 per student

Steps

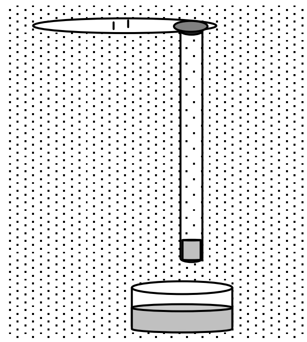
- Give each student a straw and a cup of water. Ask them to put the straw in the water and place one finger over the top of the straw. Then they should lift the straw out of the water. What happens? *(The water should stay in the straw.)*
- Can they turn the straw at different angles? *(Yes.)* Can they turn it upside down? *(Yes.)*
- Will the water stay in the straw if you put the straw in a taller glass, completely under water, and pick it up with water filling the entire straw? *(Yes.)*



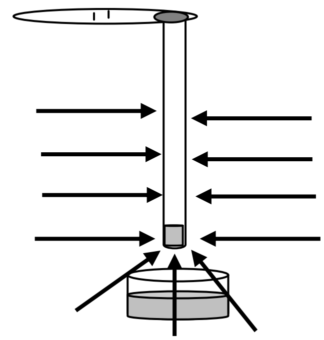
- Ask, "Given what you know about air pressure, what do you think is going on?" Collect a few ideas.
- Have students draw a model based on what they learned about air pressure in this lesson.
- Discuss their models in terms of the nature of pressure and whether this offers convincing evidence that it is omnidirectional as opposed to unidirectional. (*Air pressure is approximately 14.75 lbs. per square inch in all directions. At this point in the module, explain to the students that the outside air pressure is pushing in all directions, including up on the bottom of the straw and therefore is holding the water in the straw. See the note below about a more complete explanation to be shared with students following Section 3.)*



Unidirectional model



Omnidirectional model using dots



Omnidirectional model using arrows

Note to Teacher: What happens in this activity is more completely explained using relational causality and Boyle's Law (which is addressed in the next section). In the case where there is still some air in the straw, some water actually drips out, but because the top of the straw is sealed off, no more air can enter. As described by Boyle's Law, the air in the straw spreads out because the volume of the air space has increased, and exerts less pressure than the air outside the straw. Thus the lower pressure air in the straw and the water pressure are less than the outside air pressure keeping the water in.

Follow-up Questions for Class Discussion

- What made sense to you about this experiment?
- What did not make sense to you?
- Is this convincing evidence that air pressure behaves in an omnidirectional manner?

Water in a Cup
(Reinforcement Activity)

In this activity, you will demonstrate what happens when a cup of water covered with an index card is inverted. You will discuss with your students what this reveals about the omnidirectional nature of air pressure.

Materials

- A plastic cup filled with water
- An index card slightly larger than the mouth of the cup

Steps

- Fill the cup full with water and place the index card on top of the cup.
- Ask: "Predict what will happen when I turn the cup upside down." Have students write down their predictions on a piece of paper.

Note to Teacher: Do the next steps over a sink or large container to catch any water drippings; also make sure that the hand holding the card is dry.

- Put one hand on top of the card and invert the cup, holding the card in place.
- Take the hand that was holding the card slowly away. (*The water should stay in the cup*.)
- Ask: "What do you think is keeping the water in the inverted cup? Write down your ideas on the piece of paper." Encourage students to include a drawing to help them to explain their idea.
- Ask: "What caused the water to stay in the cup when it was upside down?" Elicit responses from the class.
- Have students discuss their responses from the initial activities with a partner. Then they should draw a model to explain what happens with the water in the cup. How have their ideas changed?

Follow-up Questions for Class Discussion

Ask:

- "What does this activity suggest about whether air pressure only pushes down or whether it pushes in other directions, too? What do you think?" Have students share their models as part of the discussion.
- "What do you find puzzling about the activity? What does and does not make sense to you?"
- "Do you think that this activity offers convincing evidence that air pressure works in all directions? Why or why not?"

Note to Teacher: The reason this activity works is because the air pressure (14.75 lbs. per square inch) acting omnidirectionally outside the cup is greater than the air pressure inside the cup. If the cup is completely full, there is no air, and therefore no air pressure in the cup, so only outside air pressure is acting to keep the water in the cup. If the cup is not completely full, then Boyle's Law is in action. As you invert the cup, some water drips out, and the volume containing the air pocket increases. However, no more air can enter the cup, so the air in the pocket spreads out to fill the available space and the air pressure is lowered. The outside air pressure is greater than the inside air pressure, so the water stays in the cup.

What is the difference between the *Water in a Straw* activity and this activity? In the straw activity, you don't need a card across the bottom of the straw because the diameter is small enough that the surface tension of the water forms a meniscus and prevents the water from dripping and the air from displacing the water. Unlike the *Water in a Straw* activity, turning the cup sideways often results in the seal to the paper breaking and the water spilling out. Theoretically, however, one should be able to turn it sideways.

"Why Does the Top Fly Off of the Teapot?"
(Reinforcement Activity)

Materials

- A plastic teapot with a lid

Steps

- Have students watch as you blow into the spout of a plastic teapot. After a few moments, the lid should pop off. Draw the students' attention to the downward direction of the spout. Ask, "Why does the top fly off the teapot?"

- Ask, "What does this demonstration suggest about the direction or directions that air pressure pushes? Does it support the commonly held idea that air pressure only pushes down? Why or why not?"

- Gather ideas. Help the students connect what they learned in this section to what they have just observed.

Note to Teacher: You may also want to have the students draw models of what they think is happening. Some students may think that the top pops off because the force of blowing moves air that somehow bounces off the bottom of the teapot and is deflected to push the top off. If students raise this possibility, be sure to discuss it as a possible explanation and try variations on the activity with different containers where the hole that you blow into is located in different spots.

The Squished Cup: Is Water Pressure Unidirectional or Omnidirectional?

(Reinforcement Activity)

The picture below is a "before and after" shot of a Styrofoam cup that was brought to a depth of 1770 ft. in the waters off the Gulf of Mexico on September 28, 1994. Have your students carefully examine the picture. Then ask the discussion questions.

Before **After**

Follow-up Questions for Class Discussion

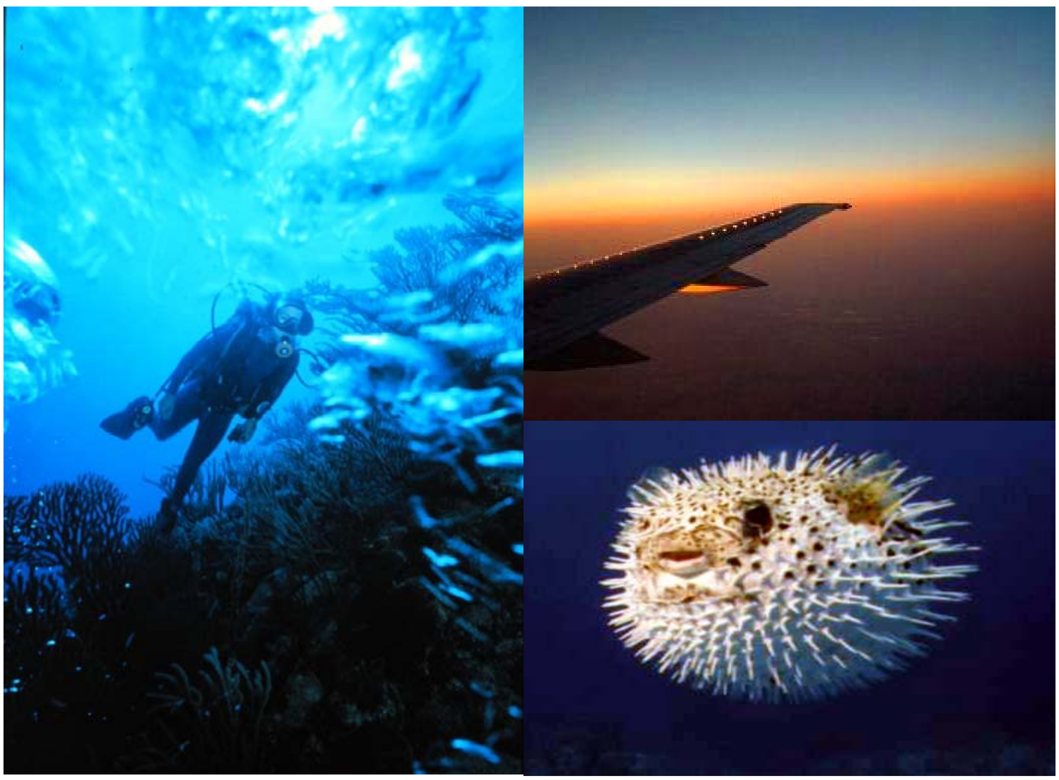
- What do you notice about the cup that was brought underwater? *(It is squished in from all sides.)*
- What might have caused the changes that you notice? *(Water pressure.)*
- Does this suggest that water pressure behaves unidirectionally or omnidirectionally? *(Omnidirectionally.)*
- Do you think that water pressure is analogous (similar in key respects) to air pressure? *(Yes.)* Why or why not? *(Its molecules exert pressure in all directions.)*

Endnotes for Section 2

[1] e.g. Wilensky, U., & Resnick, M. (1999). Thinking in levels: A dynamic systems approach to making sense of the world. *Journal of Science Education and Technology, 8*(1), 3-19.

[2] Hewitt, P.G. (1987). *Conceptual Physics*. Menlo Park, CA, Addison Wesley.

SECTION 3
RELATIONAL CAUSALITY



This section addresses students' tendency to apply simple linear causal structures to pressure-related phenomena such that they miss the complexity involved. The concept of relational causality is introduced to help students to understand that often a relationship of higher and lower pressure accounts for pressure-related outcomes. Boyles' and Charles' Law are introduced and interpreted using relational causality.

Section 3
Table of Contents

Explanation of Photographs on Preceding Page

A *scuba diver* has to pay careful attention to *relational causality*—specifically, the relationship between the pressure on the outside of his or her body, and the pressure on the inside of his or her body pushing out. As a scuba diver descends, the external water pressure on the body increases. To compensate, the diver breathes air from a scuba tank at high pressure. In response to the external pressure, the blood pressure inside the body also increases. When the diver ascends, he or she must exhale. Otherwise, with the high air pressure in the lungs staying relatively constant, and the body pressure (especially blood pressure) decreasing, it is possible to rupture one's lungs and introduce air bubbles into the blood. If the air bubbles circulate to the heart or the brain, the diver could die. Exhaling helps to keep the lung and blood pressures equalized. *(Photo Credit: National Oceanic and Atmospheric Administration/Department of Commerce.)*

Puffer fish are able to increase their volume by taking on gulps of water or air (most typically water). This increased matter causes increased pressure against the insides of the fish, and when the pressure is greater than the surrounding water pressure, the fish expands, as explained by a *relational causal model*. Once a puffer fish is inflated, it becomes very hard for a predator to eat it. *(Photo Credit: Louise Seddon)*

The flight of an *airplane* is explained by the *relational causality* involved in Bernoulli's principle. Faster moving air over the curved surface of the top of the wing exerts less air pressure than that traveling over the relatively flatter surface of the bottom of the wing, resulting in a pressure lift.

Lesson 5
Contrasting Linear and Relational Causality in Explaining Air Pressure Phenomena

This lesson draws students' attention to the relational causality involved in many pressure–related phenomena. Students are engaged in an activity where air pressure acting on both sides of a bag influences whether students can push or pull on the bag.

Understanding Goals

Subject Matter

- ❖ Differences in air pressure can cause effects. Areas of higher pressure move towards areas of lower pressure until equilibrium is achieved.
- ❖ A change in the amount of force or the area over which that force is applied results in a change in air pressure.
- ❖ When the air pressure within an object and the outside air pressure are equal or balanced, it is difficult to notice the effects of air pressure. When the air pressure within an object and the outside air pressure are unequal or unbalanced, we are more likely to notice the effects of air pressure.

Causality

- ❖ Air pressure-related phenomena are often best explained using a relational causal model.
- ❖ In a relational causal model, what happens is due to a relationship between two variables—often a relationship of balance or imbalance.
- ❖ Most people lapse back into a linear model of thinking about cause and effect, and this can make it hard to understand how air pressure acts.
- ❖ When our current models do not explain our observations of a phenomenon, we need to re-evaluate either our model or our observations. Often, we need to discard our current model for a model with a better explanatory fit.

Background Information

Relational Causality

In relational causality, a relationship between two variables accounts for an outcome. Therefore, it is not enough to consider one variable or the other, both must be considered in relation or in comparison to each other. For example, two girls can be sisters but neither girl alone is the "cause" of being sisters. It is the relationship between the two that "causes" them to be sisters. You *can* make comparisons about the relationship. For example, you can say that one sister is older and one is younger, but this only makes sense in terms of their relationship, and in comparison to each other.

In science phenomena, relational causality often applies when two amounts of something are being compared, such as the densities of two liquids, or amounts of pressure. Typically, the outcome is due to balance or imbalance between two variables.

Reducing Relational Causality to Linear Causality

Students often reduce instances of relational causality to simple linear causality. For instance, when explaining why liquid rises when drinking from a straw, they may say something like, "Suction makes liquid go up the straw." It is also common for students to use token explanations where words common in the everyday world of science (such as 'static electricity', 'air pressure', or 'vacuum') are given as an agent or mechanism, as in "air pressure makes it happen." When pushed, students rarely have deep understanding that they can use to elaborate on the statement. Listen for instances when students give simple linear explanations or use token explanations in assigning cause in air pressure situations. Press them for their understanding of the words they use, and steer them towards a more thoughtful, reflective causal model to explain their observations.

To fully understand the effects of air pressure on an object, the air pressure inside an object must be compared and contrasted with the air pressure outside the object. Often, students focus solely on the air pressure inside the object or outside of the object, rather than considering the interaction or relationship between the two. When students only consider one side of the relationship, they lose important aspects of the causal story, which can limit their understanding of air pressure and pressure-related events.

Lesson Plan

Materials

- ➢ Jar, wide-mouthed, 1 per pair of students
- ➢ Plastic sandwich bags, 2 per pair of students
- ➢ Thick rubber band, 1 per pair of students
- ➢ *Modeling the Jar and the Bag* activity sheet, 1 per student
- ➢ *Thinking About Relational Causality* sheet, 1 per student

Prep Step

- ➢ Review the lesson plan, background information, and understanding goals.
- ➢ Photocopy the activity sheet, *Modeling the Jar and the Bag* (p. 107).
- ➢ Assemble a set-up of the jar, plastic bag, and rubber band before class.
- ➢ Photocopy the sheet, *Thinking About Relational Causality* (p. 111).
- ➢ Read the *Picture of Practice* (p. 74).

Analyze Thinking

Step 1: Exploring a Pressure-Related Phenomenon that Involves Relationality

Introduce a simple problem involving relational causality that many students already think that they know the explanation for.

- Show students a garbage bag inflated with air.
- Have them take turns trying to push their fist into the garbage bag. Are they able to? Why or why not?
- Ask, "What do you think is going on?"

Students may realize that there is air in the bag and may say that the air takes up space. Explain that the activity that they do next will help them think about what is happening with the inflated garbage bag in a more complex way.

RECAST Thinking

Step 2: Modeling the Jar and the Bag Activity

Have students work in pairs to do the *Modeling the Jar and the Bag* activity. The activity provides students with an opportunity to consider relational causality. In the activity students:

- Construct a model to explain what prevents a bag sealed to the outside rim of a jar from entering the jar.
- Construct a model to explain what prevents a bag that is placed into a jar and then sealed to the outside rim of the jar from being pulled out of the jar.
- Consider the relationship between the air inside the jar and outside the jar.
- Complete the questions that go along with the activity.

Note to Teacher: As students are doing the activity, make sure they have the bag sealed securely with a thick rubber band in order to feel how difficult it is to pull the bag out of the jar or push the bag into the jar.

As students finish up the activity, encourage them to think about how air pressure played a role in preventing them from pulling the bag out of the jar and pushing the bag into the jar.

Explore Causality

Step 3: Sharing, Discussing, and Critiquing Students' Models for Explaining the Jar and the Bag Activity

Have students share their models. Explain the guidelines for discussing models before you begin.

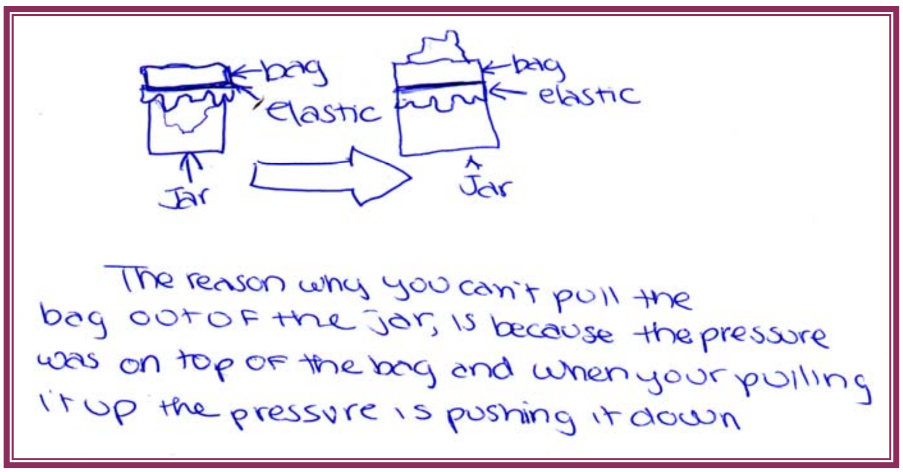
- All ideas are valued.
- When your model is critiqued, it is not intended to be personal. Rather, models are critiqued for the learning benefit of the class as a whole.
- The critique must begin with positive feedback. The class should discuss what is helpful about each model.
- After positive feedback, provide constructive criticism. Constructive criticism focuses on what would make the model work better. The class should discuss what the model is missing and what might limit someone's understanding of it.

Tell the class that scientists critique, change, and discard models frequently. This is how they share their findings with each other, learn from one another, and push their scientific understanding forward.

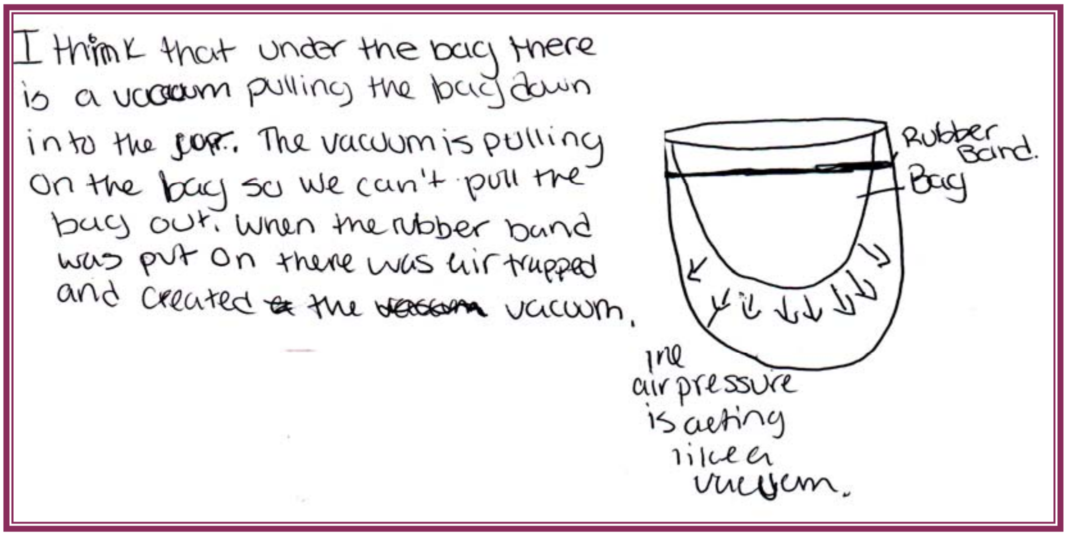
Invite students to draw their models from the activity, *Modeling the Jar and the Bag*, on the board. Include students who had both linear and relational models.

Examples of Students' Models

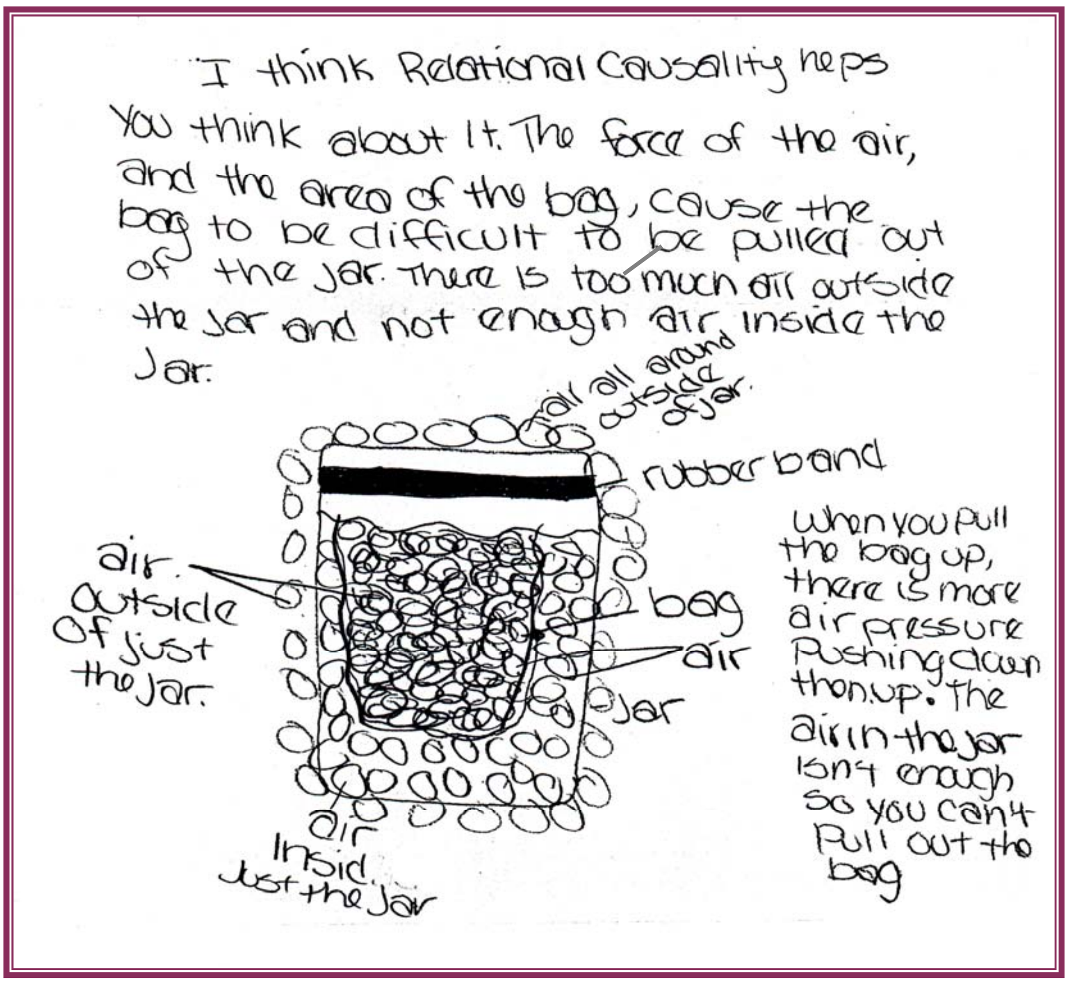
Linear Causal Model (focused on outside pressure)



Linear Causal Model (focused on inside pressure)



Relational Causal Model



Note to Teacher: Some students might say it happens "because of a vacuum." Substituting a label for an explanation is a kind of token explanation that can signal shallow understanding. When students use token explanations, push them to explain what they mean by the words they use. Ask: "What do you mean by a 'vacuum?' What is going on?" Ask them to explain their answers at a deeper level. Most will not know how to conceptualize a vacuum beyond thinking about it as an entity. Once they are able to consider a relationship as the cause of what happens, they should begin to understand that what is going on is a process, not a "thing."

In the next lesson, students will learn about Boyle's Law which helps to explain what is going on. As you pull the bag out of the jar, you lower the air pressure in the jar and create a differential with higher pressure outside the jar than in it.

Step 3: Discuss the Models in Terms of Causality

Discuss the students' models, and how some reflect a linear causality while others reflect a different form of causality.

- Ask, "Do you see some models that have a linear form, where one thing makes another thing happen? For instance, a vacuum makes something happen, or the air outside the jar makes something happen?"
- Encourage students to notice linear aspects of their models. If they have difficulty, point out the aspects that you see and explain what makes them linear.
- Ask, "Do you see some models that do not have a linear form, where there is a relationship between two or more variables that contributes to the outcome?"
- Encourage students to see that some of their models involve a relationship between inside and outside air pressure. If none of the models have this aspect, draw and explain one.

Note to Teacher: Be sure not to shortchange this discussion. It offers an important basis for the rest of the section.

Step 4: Introduce Relational Causality

- Hand out the sheet, *Thinking About Relational Causality*, to read and discuss.
- Ask: "Does this help you to think about what is going on in any way?"
- Discuss students' ideas.

Make sure that students see relational causality as more than just two contributing causes (in an additive sense). The crucial piece is that you have two variables in relation to each other (higher/lower, more/less, etc.) that contribute to the outcome. You should be able to compare the values of the two variables.

Review, Extend, Apply

Step 5: Revisit Students' Models in Terms of Linear and Relational Causality

Help students apply what they have learned about relational causality to the activity that they just completed. Ask:

- "In what ways does a linear causal model fail to explain what happens in the jar and bag activity?" *(It doesn't account for the air pressure that is both inside and outside the jar, and the relationship between them.*)
- "Do you think the jar and bag activity is a good example of a relational causal model? Why or why not?"
- "Is relational causality involved in the garbage bag problem presented at the beginning of class?"
- "What are some other relational causal stories that you can think of?"

PICTURE OF PRACTICE

Linear Versus Relational Causality: An Eighth Grade Science Lesson

This lesson describes how students explore linear and relational causality within the context of air pressure. Here, the bag and jar activity is used as a demonstration, as opposed to being done independently by students. However, you might overhear your students expressing similar ideas to those expressed below. This lesson addresses the idea that a linear model is inadequate for explaining why a baggie sealed onto a jar cannot be pushed into or pulled out of the jar.

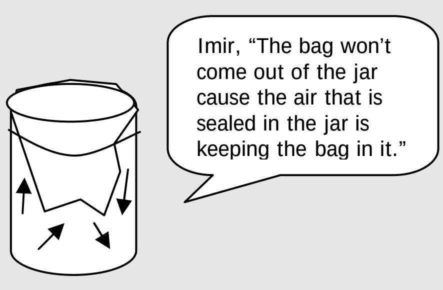
Mrs. B. sets up the jar and plastic sandwich bag demonstration in front of the class. The class watches as she seals the bag onto the jar with a thick rubber band.

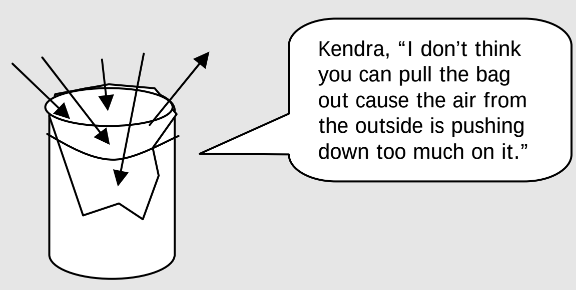
- Mrs. B: I've sealed this bag to the jar as you can see (she shows the setup to the class). I would like for someone to try to pull the bag out of the jar.

Mrs. B. walks over to Sarah. Sarah puts her hand into the jar and surprisingly finds she cannot pull the bag out.

- Sarah: I can't!
- Mrs. B: Why won't the bag come out of the jar?
- Rachel: It's a vacuum. ← Token explanation
- Brian: It's a suction cup.
- Mrs. B: What do you mean by vacuum, Rachel?
- Rachel: Well you can't take it out cause it's sucking it in cause there's like air in there…it's weird.
- Mrs. B: How many of you think there is a vacuum inside there? What is a vacuum?
- Kobe: It sucks something up, like a vacuum cleaner.
- Mrs. B: How does it "suck something up?"
- Kobe: I don't know, it just does.
- Mrs. B: Often when we are asked to explain what causes something, we use words such as "vacuum" that we cannot fully explain. What do you think is really happening? Can you explain why the bag won't come out of the jar without using words such as "vacuum" or "suction cup"? Why don't you take a minute to draw out your ideas?

Mrs. B. goes around the room as the class is drawing out their ideas. She notices that Imir's picture is focusing what is happening inside the jar while Kendra's picture is focusing on what is happening outside of the jar. She asks them to put their models on the board for the class.





PICTURE OF PRACTICE
Continued from previous page

- Mrs. B: So what do you think of Imir's model and Kendra's model?
- Ned: Imir focused on the air inside and Kendra focused on the air outside.
- Nancy: If Imir's model is correct and the air is applying pressure to the bag, shouldn't it come out of the jar?
- Beth: Yeah, and if Kendra's model is right, shouldn't the bag get pushed into the jar?
- Mrs. B: Good points Nancy and Beth. Do you see what they mean class? Both Imir and Kendra used a linear model to explain their ideas. What do you think I mean by linear model?
- Jarrod: Well, something linear goes in one direction.
- Mrs. B: Right. So looking at their models, how can they be considered linear?
- Jarrod: Well, Imir's model looks at what's happening from the inside of the jar and Kendra's model looks at what's happening from the outside of the jar.
- Mike: Wouldn't you need to look at both to really explain what's happening?
- Mrs. B: Explain what you are thinking, Mike.
- Mike: Well, there's still air left inside the jar and you're trying to pull the bag out but the air's going into the jar too, it's pushing it in so you can't take the bag out.
- Mrs. B: Mike is reasoning about this in terms of a relationship. Many things that we talk about with air pressure involve a relationship. Although Imir and Kendra's models were good, they each only looked at one side of the relationship—they were linear. Sometimes linear models can be used to explain things, but at other times, you need to think about what is happening in terms of a relationship. Was there something you wanted to add, Sarah?
- Sarah: So, the air left in the jar is pushing the bag out and the air outside the jar is trying to push the bag in so that way you can't take it out, right?
- Mrs. B: Is this an equal relationship or is one greater than the other?

Mrs. B. hears a mix of responses from the class.

- Mrs. B: (referring to Imir's drawing) So you could expand this drawing to show that if you took the bag out, say from here to here, we sealed that bag around the jar, right? There's this air inside the jar; when you went to pull that bag out, did the amount of air in the jar change?
- Kendra: No.
- Mrs. B: What happened to it?
- Kendra: It expanded?
- Mrs. B: What do you mean by 'expanded'?
- Kendra: It spread out.
- Mrs. B: What does that cause?
- Yao: It causes less air pressure because there is the same number of molecules bouncing around in more space—so they can't make as much pressure.
- Gwyn: So the air pressure outside is more and prevents you from pulling it out of the jar.

PICTURE OF PRACTICE

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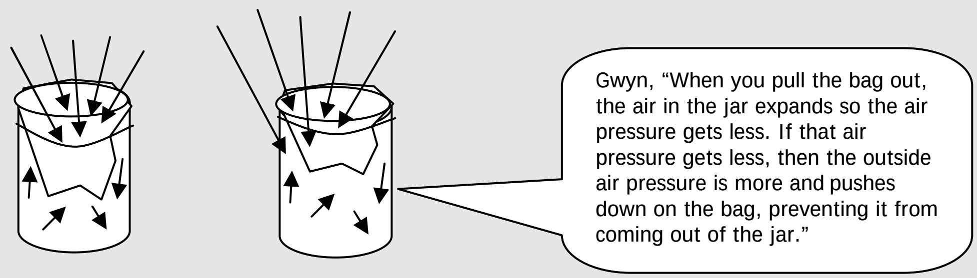
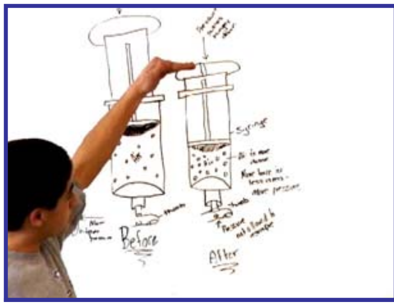
- Mrs. B: Can you draw a model of that on the board for the class Yao or Gwyn?



After discussing Gwyn's relational model, the class moves on to the next demonstration, in which a bag sealed to the outside of the jar cannot be pushed into the jar.

Demonstration of Pulling the Bag Out of the Jar



Lesson 6
Applying Relational Causality to Reasoning About Boyle's Law

This lesson focuses on Boyle's Law. Students apply a relational causal model in which they focus on how air pressure and volume within a closed system are related. They also apply Boyle's Law to situations beyond closed systems.

Understanding Goals

Subject Matter

- Although the relationship between force and surface area defines air pressure, both volume and temperature affect air pressure.
- Boyle's Law states that at a constant temperature, the pressure times the volume of an enclosed gas remains constant. When one increases, the other decreases to maintain equilibrium.
- An increase or decrease in volume (and the resulting decrease or increase in pressure) is often the result of an air pressure differential between the inside and the outside of an object.

Causality

- A relational causal model can be used to understand Boyle's Law.
- When our current models do not explain our observations of a phenomenon, we need to re-evaluate either our model or our observations. Often, we need to discard our current model for a model with a better explanatory fit.

Background Information

The Relationship Between Pressure and Volume (at a Constant Temperature)

Understanding pressure-related phenomena involves being aware of different variables and the relationships between them, and reasoning about these variables systematically. Scientists analyze the behavior of a system to see what rules govern its behavior. They have discovered several laws that nature consistently follows in relation to air pressure. One such law is explored in this lesson. Boyle's Law states that at constant temperature (T), the pressure (P) times the volume (V) of an enclosed gas remains constant. In formulaic terms:

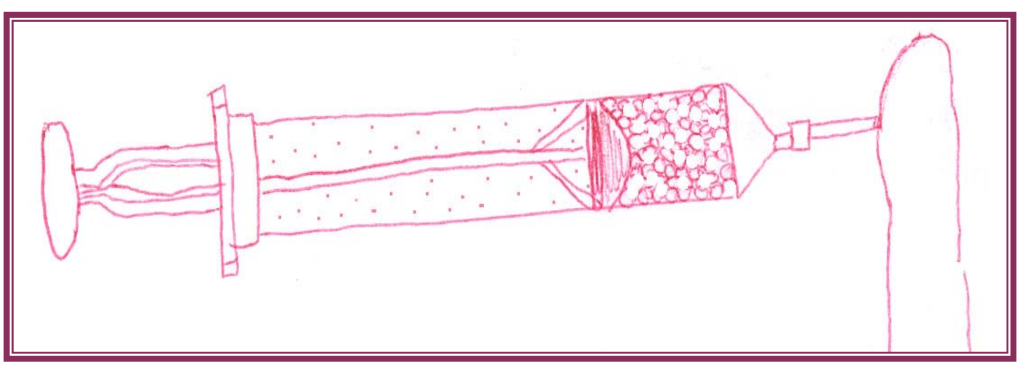
PV = k, where k equals some constant value and T is unchanging. Thus, when one increases, the other decreases. A relational causal model nicely demonstrates this. According to Boyle's Law, if the volume increases then the air pressure should decrease to maintain the constant value, k. Let's look at the relationship between force and area more closely. Remember that

$$P = \frac{F}{A}$$

If the original force is 4 and the area is 2, then the air pressure is 2 ($\frac{4}{2} = 2$). We know that if the volume of an enclosed gas increases, then the area must also increase (for example, to 4). Therefore the air pressure does indeed decrease, to 1 ($\frac{4}{4} = 1$), when the volume increases.

Using a Syringe to Demonstrate Boyle's Law

Boyle's Law can be demonstrated with a syringe, the device with a plunger and a barrel to which doctors attach a needle to draw blood samples or give injections. When the plunger is drawn back on the syringe, the volume inside the barrel increases. This decreases the pressure of fluids (such as air or liquids) on the inside of the syringe. The atmospheric pressure outside of the syringe remains unchanged and therefore is greater. The pressure differential that is created forces fluid to enter the syringe. Pushing in the plunger of the syringe decreases the volume inside the barrel, thus increasing the inside pressure. This makes the internal pressure greater than the outside atmospheric pressure. The pressure differential pushes fluids out of the syringe. However, if you hold one of the variables (such as force) constant, you can experience Boyle's Law first-hand. If you cover the opening of the syringe with your finger and then pull the plunger back, the molecules in the fluid inside the syringe spread out to fill the available space. To accommodate the increase in volume, pressure decreases proportionally, and you can feel your finger being "pulled" into the syringe a bit. Conversely, if you draw back the plunger, then cover the opening with your finger, and depress the plunger, the same amount of fluid must fit in a smaller space. Therefore the molecules are pushed closer together, the pressure increases to accommodate the decrease in volume, and you feel the resulting "push" on your finger.



Boyle's Law is in Action Around Us Everyday

There are many examples of Boyle's Law in action around us everyday. For instance, if we step on an inflated balloon or push in on a bubble in a piece of bubble wrap, we decrease the volume and thus increase the pressure inside until it is too great for the outer membrane, and the balloon or bubble pops! When we pump up a bicycle tire, we force air into the tire and the volume of the tire increases to accommodate the additional air without increasing the pressure (until the tire cannot expand any farther and then the pressure increases). Every time we take a breath, the muscle located just below the lungs (called the diaphragm) moves downward, increasing the volume in the lungs. This results in decreased air pressure inside the lungs relative to the atmospheric pressure, which forces outside air into the lungs. Exhaling moves the diaphragm upward, decreasing the volume of the lungs and correspondingly increasing the air pressure inside the lungs as compared to the air pressure outside the lungs. This imbalance in pressure pushes waste gases from respiration out of the lungs. In order to avoid being eaten, a Puffer Fish takes on water (or sometimes air), which increases its volume to maintain a constant pressure, despite the added fluid. If you begin to fill your cheeks with air, your cheeks will expand until they have as much volume as they can accommodate. If you continue to add air beyond this point, you will feel increased pressure. As these examples illustrate, Boyle's Law explains many everyday phenomena. Try to come up with a few examples of your own.

Lesson Plan

Materials

- Plastic syringes, 1 per pair of students
- *How Does a Syringe Work?* activity sheet, 1 per student
- Optional Video, *Investigations in Physics: Pressure*. (1997). Princeton, NJ: Films for the Humanities and Sciences.
- Optional Computer Simulation, *Atomic Microscope 3*-D, available at: http://www.starkdesign.com/products/ or *Virtual Molecular Dynamics Laboratory* available at http://polymer.bu.edu/vmdl

Prep Step

- Review the lesson plan, background information, and understanding goals.
- Photocopy the activity sheet, *How Does a Syringe Work?* (p. 113).
- If you decide to do the Reinforcement Activities, be sure to order the video and download the computer simulation well before the day of the lesson.

Analyze Thinking

Step 1: Thinking About Volume and Pressure

Ask your students to recall what they discovered during the *Modeling the Jar and the Bag* activity, when they tried to pull the bag out of the jar and to push the bag into the jar.

Next, ask them to do a "thought experiment." When the bag was sealed inside the jar, if they were strong enough (and the bag was strong enough) to overcome the differential in air pressure and they COULD pull the bag out of the jar, what would happen to the air inside the jar? Don't collect ideas at this point; rather, have students consider what they think would happen.

RECAST Thinking

Step 2: Exploring the Relationship Between Pressure and Volume

Explain to your students that they will do an activity to help them think about what happens in situations when volume is increased but no additional air is able to enter the enclosed space (as was the case when trying to pull the bag out of the jar).

- Pass out the activity sheet, *How Does a Syringe Work?* to each student.
- Have students pair up to complete the syringe activity.

During the activity, students will:

- Draw a model to show what the air looks like in a syringe before compression.
- Draw a second model to show what the air looks like in a syringe after compression.
- Explain their observations using relational causality.
- Describe an example of relational causality from their own lives.

Note to Teacher: Note whether students realize that the amount of air in the syringe is the same as before, only compressed in less space. If students' models contain a different amount of air after compression, challenge them to think about whether more air can enter or if the amount was conserved, and what happened to the air when it was compressed.

Give students about 25 minutes to work on questions 1 through 4 on the activity sheet. They will answer question 5 following the class discussion.

Step 3: Discussing Students' Discoveries

Bring the students back together as a group to discuss what they discovered.

Have two students put their models on the board and explain how their ideas changed as they progressed from one model to the next (*see examples of students' models at the end of this lesson, pages 83 and 84*).

Gather feedback on students' models. Ask:

- Why are you able to increase the volume with the syringe but not with the plastic bag? Gather ideas. (*The bag would rip; because the syringe is hard plastic, you can force it.*)
- What happens to the amount of air in the syringe when you compress it with your finger over the top? Gather ideas. (*The amount of air stays the same even though the space it takes up is less.*)
- What happens to the air pressure in the syringe when you compress it with your finger over the top? Gather ideas. (*The air pressure increases.*)
- What happens to the amount of air in the syringe when you decompress it with your finger over the top? Gather ideas. (*The amount of air stays the same even though it takes up more space.*)
- What happens to the air pressure in the syringe when you decompress it with your finger over the top? Gather ideas. (*If you can decompress it, the pressure decreases.*)
- If the outside air pressure changed, would it affect the air inside the syringe? Would it be obvious? (*If the syringe is made of hard plastic, the shape of the*

syringe would not change, but there would still be an air pressure differential present. That is what the students feel when they push the plunger back into the syringe—the resistance due to the air pressure differential. The higher pressure inside is trying to equalize with the lower outside pressure.)

- What do you think would happen if a hole was poked in the syringe? (*The air would rush out, equalizing with the outside air pressure.*)

Explore Causality

Step 4: Introducing Boyle's Law Through Relational Causality

Discuss what happens in terms of relational causality:

- Ask, "What does this tell us about volume and air pressure in terms of relational causality?" (*That volume and air pressure are related and that as one increases the other decreases.*)
- Explain that scientists have a rule to explain what happened with the syringe activity. It is not often expressed in terms of a model or drawing, as we have seen in other lessons. Rather, the model is expressed as a law that fluids (either liquids or gases) consistently follow.
- Tell the students: Boyle's Law is used to predict the behavior of fluids in a closed container when either the volume or pressure of the fluid is changed (at a constant temperature). The law predicts that if the volume of a fluid is increased, the pressure is decreased and vice versa.

Review, Extend, Apply

Step 5: Thinking About Instances When Boyle's Law Applies

Make sure the students understand that Boyle's Law explains what is going on inside a closed container, not the relationship between the inside and the outside air pressure of the container. However, the two are related because the air pressure differential that is created due to an increase or decrease in volume within the container is in relation to the outside environment.

Ask students to think about other instances where they have observed Boyle's Law in action in everyday life. Encourage them to come with some examples. For instance, if you take a partially filled balloon and tie it halfway down the length of the balloon, it will have more pressure than if the molecules that make up the air are spread out in the entire space. Then, they should choose an example and illustrate it under Question 5 on the activity sheet.

Example of Students' Work

How Does a Syringe Work?

Name Kirsten

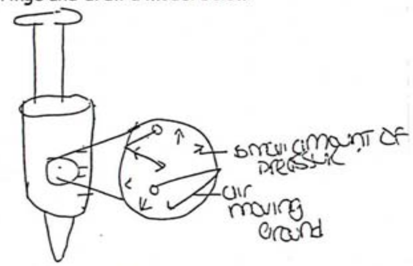
Purpose: To experiment with the relationship between air pressure and volume as defined by Boyles' Law.

Materials

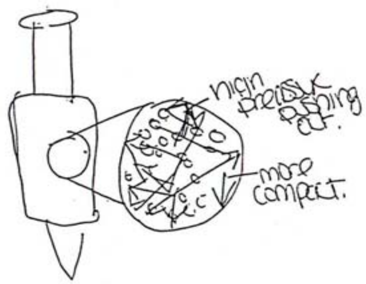
- One syringe

Directions

1. Place your thumb over the tip of the syringe. Envision what the air looks like inside the syringe and draw a model below:



2. Holding your finger over the tip, push the plunger in on the syringe to decrease the inside volume to half the original volume. Draw what the air in the syringe looks like now.



How Does a Syringe Work?

Name Conor

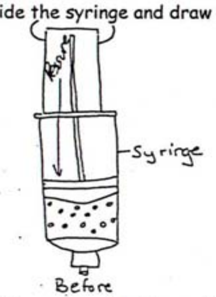
Purpose: To experiment with the relationship between air pressure and volume as defined by Boyles' Law.

Materials

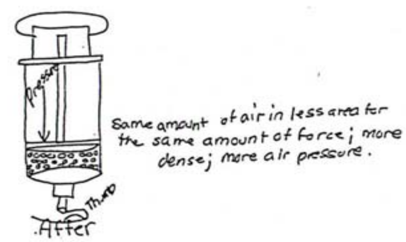
- One syringe

Directions

1. Place your thumb over the tip of the syringe. Envision what the air looks like inside the syringe and draw a model below:



2. Holding your finger over the tip, push the plunger in on the syringe to decrease the inside volume to half the original volume. Draw what the air in the syringe looks like now.



Note to Teacher: Notice that Conor gives a very clear description of what is happening with a syringe. Some students also depict movement in the molecules. Kirstin's model offers a good example.

How Does a Syringe Work?

Name Dinesh

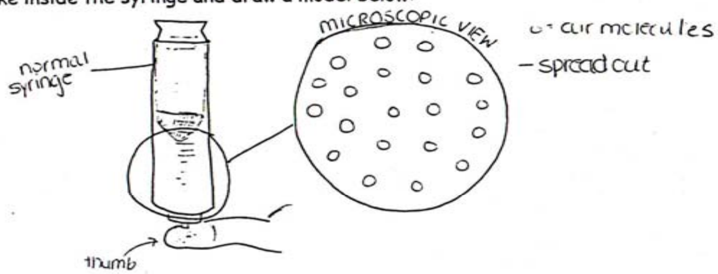
Purpose: To experiment with the relationship between air pressure and volume as defined by Boyles' Law.

Materials

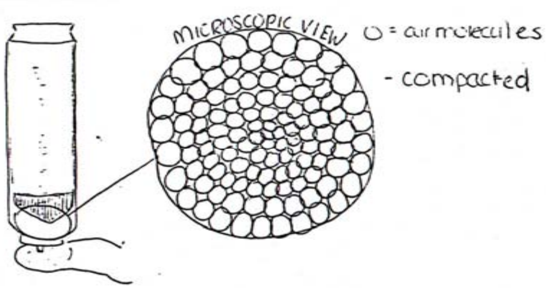
> One syringe

Directions

1. Place your thumb over the tip of the syringe. Envision what the air looks like inside the syringe and draw a model below:



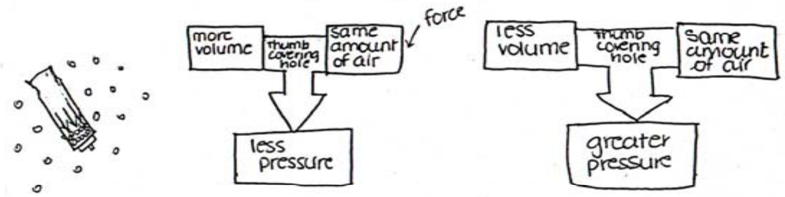
2. Holding your finger over the tip, push the plunger in on the syringe to decrease the inside volume to half the original volume. Draw what the air in the syringe looks like now.



Write a few sentences about what you think is happening in this situation in terms of air pressure.

In this situation, I believe that in the second step of the procedure, the pressure was greater because we reduced the area.

4. Does your model above show what happens in terms of a relational causal model? If not, add to it, revise it, or draw a new model below.



5. Choose an instance from everyday life that illustrates Boyle's Law. Then, using relational causality, draw a model of what is going on in the instance you chose. Label your model and write a brief explanation of what happens below it.

Model:

Brief explanation:

When you go skiing, you use a longer ski to minimize the pressure your body force exerts on the ski. If you used a smaller ski, it wouldn't be nearly as affective.

Note to Teacher: Dinesh depicts air pressure using dots. She does not indicate that the dots are in motion. Her model suggests that she understands that reducing the volume in the syringe results in compacting the molecules that make up the air (however, she has drawn them to resemble a liquid more than a gas) and that the air pressure will increase. Her transfer example, in number 5, recognizes the relationship between volume and area (even though it is a pressure example instead of an air pressure example.)

Lesson 7
Reasoning About Air Pressure Differentials Using Relational Causality

This lesson forces students' attention to the relational causality involved in drinking from a straw by offering cases with modifications that illustrate how a linear causal model falls short.

Understanding Goals

Subject Matter

- ❖ A change in the amount of force or the area over which that force is applied results in a change in air pressure.
- ❖ Air pressure is dynamic, not static.
- ❖ Differences in air pressure can cause effects. Air from areas of higher air pressure moves towards areas of lower air pressure until equilibrium is achieved.

  Note to Teacher: It is important not to substitute the word 'changes' for 'differences' here. If both sides of the relationship change in proportion to each other, then it will still be at equilibrium.

- ❖ When the air pressure within an object and the outside air pressure are equal or balanced, it is difficult to notice the effects of air pressure. When the air pressure within an object and the outside air pressure are unequal or unbalanced, we are more likely to notice the effects of air pressure.

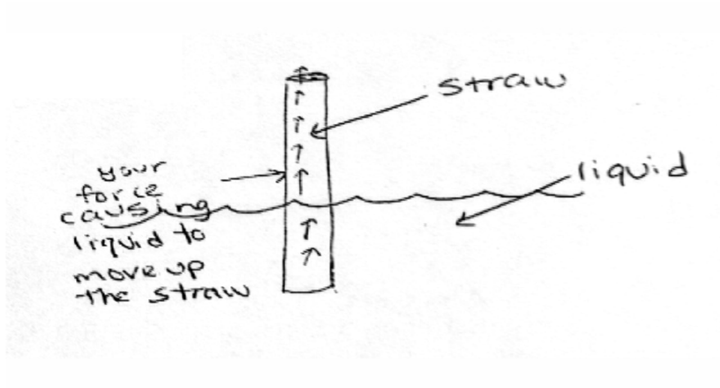
Causality

- ❖ Using a relational causal model is important for understanding a variety of scientific phenomena, including many which have to do with air pressure.
- ❖ Most people tend to lapse back into a linear model of thinking about cause and effect, and this can make it hard to understand pressure-related phenomenon.
- ❖ When our current models do not explain our observations of a phenomenon, we need to re-evaluate either our model or our observations. Often, we need to discard our current model for a model with better explanatory fit.

Background Information

Students' Default Interpretations are Typically Linear

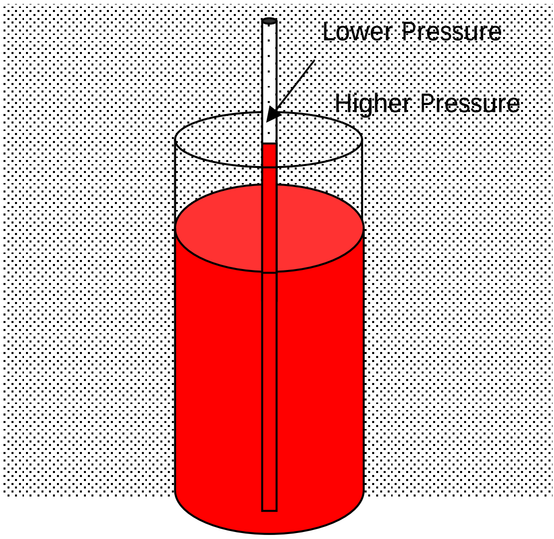
What makes a liquid go up a straw when you suck on it? Students often answer this question using a simple linear causal model where one thing directly makes another thing happen. So for instance, "sucking makes the liquid go up the straw" or "a vacuum is formed and it pulls the liquid up into your mouth."



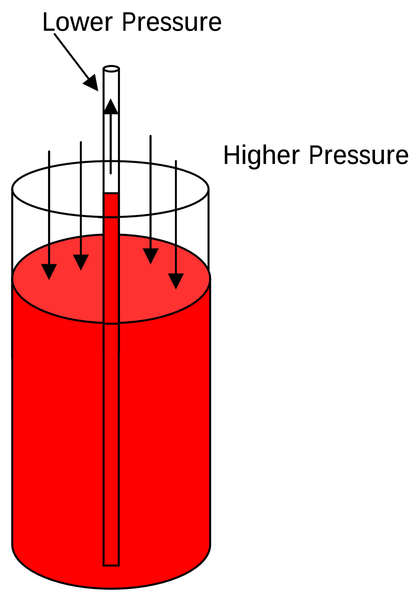
Revealing Relational Causality Behind Drinking From a Straw

The activity in this lesson reveals to students that a relational causality is in play. When you drink from a straw, you lower the air pressure inside the straw and so the relatively higher atmospheric pressure surrounding the straw pushes the liquid up. The result is due to an air pressure differential.

Relational Models

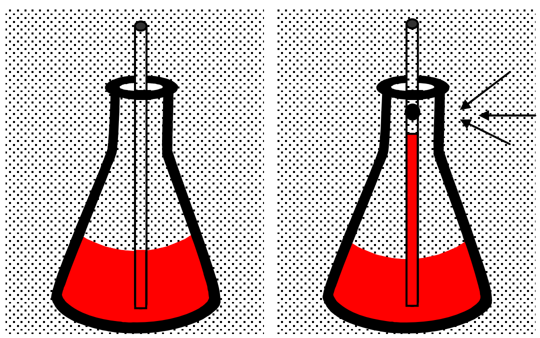


This model uses dots to depict higher and lower pressure.

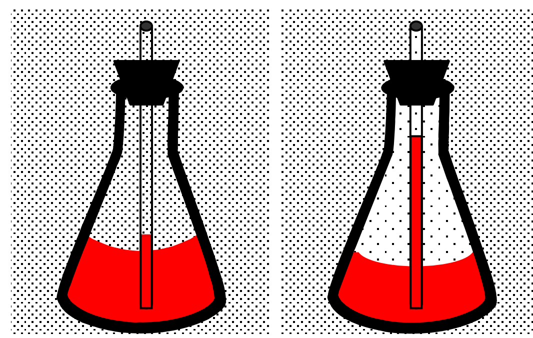


This model uses arrows to depict higher and lower pressure.

So how does the activity work and in what way does it reveal the relational causality? The activity uses three flasks with straws. Flask A is just like the straw on page 86. However, Flasks B and C are modified. Flask B's straw has a hole just below where it sticks out of the flask. This makes it impossible to lower the air pressure inside the straw because as air is removed, more air rushes in to take its place. Therefore, you cannot achieve a differential in air pressure. Flask C has a stopper on the top. Therefore, initially it is possible to remove a certain amount of liquid from the straw. However, this has the effect of decreasing the air pressure in the flask. Liquid is removed, but because it is a closed system, no air can enter to take its place, so the remaining air spreads out to take up the available space, an example of Boyle's Law. Thus, air pressure is lowered in the flask (and in the straw) and no differential can be achieved.



Flask B Before and During



Flask C Before and During

As students begin to analyze why these modified flasks won't work, the relationship between higher atmospheric pressure and lower pressure inside the straw is revealed. In all of these conversations, an emphasis is put on the relational aspects, so the terms "higher" and "lower" are used rather than "high" and "low."

Note to Teacher: Students work in groups of three for this activity. However, if you have enough supplies, you might consider having each student try each of the three flasks so that they have direct experience with the effects of each modification.

Lesson Plan

A video clip that details portions of this activity is available online at:
http://pzweb.harvard.edu/Research/UnderCon.htm

Materials

- Erlenmeyer flasks, 250 ml, 3 per group
- Juice (a color that is easy to see such as grape, cranberry, or orange juice), 450 ml per group
- Petroleum jelly, 1 jar per multiple classes
- Pin, 1 per class
- Single-holed rubber stopper (size #6½), 1 per group
- Straws (chosen to fit tightly through the size #6½ stopper hole), 3 per group
- *Drinking from a Straw: Models to Reveal What Happens* activity sheet, 1 per student

Prep Step

- Review the lesson plan, background information, and understanding goals.
- To prepare for the activity, do the following for each group:
- Label the Erlenmeyer flasks, A, B, and C.
- Fill the Erlenmeyer flasks to the 150 ml line with juice.
- Place a straw in Flask A.
- Make a small non-obvious hole in another straw, so that when the straw is in the flask, the hole will be just below the top of the flask. Place the straw in Flask B.
- Insert a third straw through the hole of the stopper. Place petroleum jelly around the hole to make an airtight seal between the straw and the stopper. Place the stopper into Flask C. If the seal is not airtight, place petroleum jelly around the stopper to seal it.
- Photocopy the activity sheet, *Drinking From a Straw: Models to Reveal What Happens* (p. 115) for each student.
- Read the *Picture of Practice* (p. 93).

Analyze Thinking

Step 1: Reflect on What Happens When You Drink From a Straw

Pass out the activity sheet, *Drinking From a Straw: Models to Reveal What Happens*. Instruct students to draw a model of what they think causes the liquid to rise in a straw when you drink from it. Give students at least 10 minutes to think through and illustrate their ideas.

Ask for several volunteers to put their models on the board (try to get a variety of models). Discuss the models and encourage the class to either agree or disagree with them. When students say things like, “a vacuum is formed,” ask what a vacuum is.

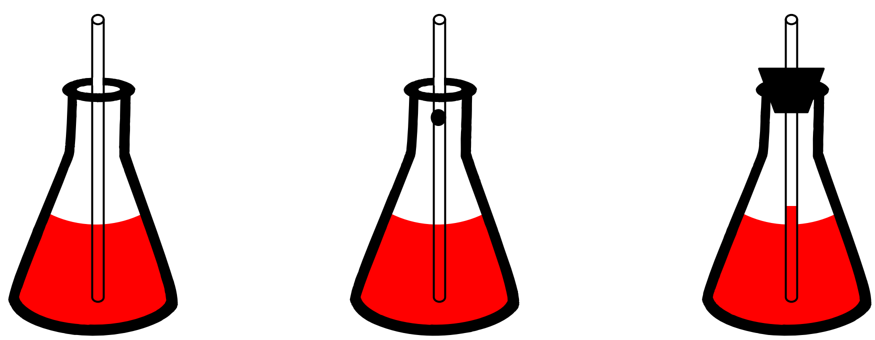
Note to Teacher: At this point, it is likely that the models will be quite similar. Most students tend to construct one-way, linear causal models to explain the event.

RECAST Thinking

Step 2: Demonstrate Why Students Might Need to RECAST Their Models

Explain to the students that they will be doing an activity to help them understand how drinking from a straw works.

- Select three students to participate in a mini-competition.
- It will begin with a demonstration. Say: “Here I have three clean flasks and straws with juice in them. You will be participating in a little competition to see who can drink the juice from their straw the fastest. You can see that there are some differences between the flasks. We’ll discuss those differences in detail later. For the student drinking from Flask C, you’ll notice something around the stopper. That is just a little petroleum jelly.”



Flask A Flask B Flask C

- Say, “When I say “go,” you are going to put your lips to the straw and begin drinking continuously. Once you have sealed your lips around the straw do not take them off or open them for air. Just breathe through your nose and drink as fast as you can. The student with Flask C should hold the stopper in place gently but not push down on it.”
- Make sure the students understand. Ask if they have any questions.
- Make sure that the rest of the class is positioned well to see the demonstration.
- Say, “Ready, Set, Go!”

Note to Teacher: The student drinking from Flask A should finish first. The student drinking from Flask B often cannot remove much liquid at all, and if the student drinking from Flask C seals his or her lips on the straw, little liquid will come up the straw.

- The students often laugh or are puzzled at the outcome. Ask each student to tell the class what it was like to drink from the straw, and to explain why he or she is laughing.
- Typically, the student drinking from Flask B says something like, “there’s a hole in my straw—no fair!” If he or she does, ask why that would matter.
- Explain the modifications to the flasks/straws. Say, “The first flask and straw setup, Flask A, has no changes and is just like when you drink from a normal straw. In the second flask and straw setup, Flask B, there is a hole in the straw just beneath the top of the flask. *(Point to it*.) The third flask and straw setup, Flask C, has a stopper and some petroleum jelly to seal off the inside of the flask. (*Point to it*.)
- Gather one or two ideas from the class about what might be happening.

Step 3: Figuring Out What is Going On

Explain to the students that they will be experimenting with and thinking about what happens with each straw and flask set-up, and analyzing what it tells them about how drinking from a straw works.

- Give each trio of students a set of three flasks as described above so that each student has one.
- Say, “Instead of having a competition, you will drink from the straws one at a time, starting with Flask A, and observe what happens. Your activity sheet asks you to draw a model of what you think is going on with Flasks B and C and to think about what evidence fits and doesn’t fit with it. Don’t forget to use each other’s minds well[1] and think together about what happens.”
- Have students work step by step through the flasks, observing, discussing, and modeling their ideas. Circulate while students are working, and ask them about their interpretations and how what they are finding out from the different flasks impacts what they think.

Note to Teacher: Some students might accidentally blow into the straw of the stoppered flask. The additional air in the flask increases the air pressure. The greater pressure causes the liquid to rise in the straw, much to the amazement of the students! In fact, it sometime shoots out and students may end up wearing the liquid. If this happens with any of the groups, make sure they think about what is going on to cause this to happen, and share their findings with the class.

Explore Causality

Step 4: Contrasting How Linear and Relational Causal Models Explain What Happens

Consider as a group what the outcomes suggest about the nature of the causality involved when drinking from a straw:

- Ask some students to put their models on the board and to explain them.
- Consider for each set of models: “What puzzling aspects do you feel that you can explain? What puzzling aspects remain?” As a group, consider some of the variables that may have been left out. “How might these affect the behavior of the liquid?”
- Draw the students’ attention to models that use relational causality as compared to linear causality. Review the definition of relational causality, “In a relational causal model, what happens is due to a relationship between two variables—often a relationship of balance or imbalance.”
- Ask, “Does one form of causality do a better job than the other of explaining what is going on?”
- Make sure that the following explanations in terms of relational causality are clear to the students:

***Flask A*:** The student draws some air into his or her mouth, thereby lowering the air pressure in the straw. The outside air pressure (atmospheric air pressure) remains constant, therefore there is a differential where the liquid moves from areas of greater pressure to areas of lesser pressure.

***Flask B*:** The hole in the straw enables outside air to enter the straw when the student is 'sucking.' This makes it impossible to achieve a pressure differential between the air outside the straw and the air inside the straw.

***Flask C*:** With the rubber stopper, there is no way for the outside air pressure to come in contact with the liquid’s surface. The student should be able to draw up some of the liquid, which lowers the pressure of the air in the stoppered flask. So while the student lowers air pressure in the straw, the air pressure in the flask is also lowered (both are lower than the outside air pressure, but are equal to each other). This makes it impossible to achieve a pressure differential.

Say, “What else could you do to further test or provide evidence for the relational causal interpretations?” Gather ideas and test them. For instance, what do the students think will happen if they blow gently into the stoppered flask? Can they find a way to get a pressure differential in this case? If they used a straw with a hole above the stopper on Flask C, what do they predict would happen? What other variations can they think of?

Review, Extend, Apply

Step 5: Making Connections to Other Pressure-related Phenomena

Ask students to think about other experiences that they have had when drinking from a straw, and to analyze what is going on. For instance, what happens when you drink from a juice box? Why do you need to take your lips off every so often? Do you ever get juice splashed on you? What might be going on? What other instances of drinking from a straw can you now explain?

Next, broaden the discussion beyond drinking from a straw and ask students to think about other experiences that involve pressure differentials—instances involving higher and lower pressures. Some examples include the pressure changes involved when going up in an airplane, or the pressure differences inside and outside of a house during a hurricane (when there is lower pressure outside and higher pressure inside).

Revisit some of the activities that students did earlier in the module. What do they think is going on with a barometer? What about when we inverted a cup full of water?

Introduce and discuss the following puzzle: "If wind is the result of a relationship between higher and lower pressure, and pressure is not forceful in the sense of having a direction, why does it feel as though it actively pushes against your face?" *(Because wind is air moving from areas of higher pressure to areas of lower pressure, it does have a direction. In a sense, it is pushed towards areas of lower pressure, and so you can feel the force of the wind on your face. Just like the liquid in the straw that gets pushed into your mouth, the air gets pushed towards areas of lower pressure.)*

PICTURE OF PRACTICE

How Do Air Pressure Differentials Act as Causes?
An Eighth Grade Science Lesson

The following picture of practice describes a lesson in which students explore what causes liquid to rise in a straw when you drink from it. One group of students is discussing their ideas with Mrs. B. about why the liquid is so hard to draw up in the stoppered flask. This lesson addresses the idea that pressure is dynamic and changes in air pressure result in many things, such as differentials that cause liquid to rise in a straw!

Mike, Emma, and Devon motion for Mrs. B. to come over to their work area.

- Mrs. B.: Do you have a question for me?
- Emma: Yeah, we're trying to figure out why the liquid is so hard to suck up in this flask.
- Mrs. B.: What ideas have you come up with so far?
- Devon: Well, we know that when you first suck on the straw, you're taking the air out of the straw, so that's making the air pressure less…but we thought that would make the liquid go up the straw.
- Mike: That was our model for the first flask. You take the air out of the straw, the air pressure gets less, and the higher outside air pressure pushes the liquid up the straw. But we don't get this one.
- Mrs. B.: Why don't you try it again?

Emma tries once again to drink from the flask and is able to draw up a small amount of liquid, but quickly begins to have problems. In frustration, she blows into the straw. Liquid immediately shoots out of the straw and onto her shirt! Mike and Devon laugh, but Emma does not look amused.

- Mrs. B.: Sorry about that Emma. I thought you said the liquid didn't come up?
- Emma: It didn't when I did it before.
- Mike: Yeah, but this time you blew into the straw!
- Devon: Hmmm. How come that worked? I wonder why.
- Emma: Well, blowing into the straw instead of sucking the air out of it added more air to the flask…
- Mike: I know what happened! Before, the air pressure wasn't high enough to push, but when Emma blew into it, it was.
- Devon: Yeah, but why wasn't it high enough before?
- Mrs. B: Emma, when you first tried drinking, were you able to get any liquid out?
- Emma: Just a little.
- Mrs. B: Okay, think about the effect of removing that liquid from the flask, which is a closed system once you put your lips on the straw. What happens?

Mrs. B. lets Emma, Devon, and Mike puzzle this out as she circulates to other groups. Together they begin to focus on how the molecules that make up the air must spread out, and the subsequent lower air pressure that results

Lesson 8
What is Charles' Law and How Does it Involve Relational Causality?

This lesson draws students' attention to how temperature is related to air pressure and introduces students to Charles' Law through the lens of relational causality.

Understanding Goals

Subject Matter

- Charles' Law can be used to predict what will happen to the volume of a fluid when the temperature is changed (at constant pressure). The law predicts that if the temperature of a fluid increases, the volume also increases, in order to maintain the same pressure. Similarly, if the temperature of a fluid decreases, the volume also decreases in order to maintain the same pressure.

Causality

- A relational causal model can be used to understand Charles' Law.
- Considering multiple relationships at various levels within pressure phenomena can be a mentally challenging task, especially when the relationships are dynamic, as is the case with pressure-related phenomena.

Background Information

Charles' Law Describes the Relationship Between Volume and Temperature When Pressure Remains Constant

Understanding pressure-related phenomena involves being aware of different variables and the relationships between them, and analyzing a given situation systematically. Scientists analyze the behavior of a system to see what rules govern its behavior. Scientists have discovered several laws that nature consistently follows in relation to air pressure. The last lesson explored Boyle's Law, which states that at a constant temperature, the pressure times the volume of an enclosed gas remains constant. When one increases, the other decreases to maintain equilibrium. The activities offered a number of examples of Boyle's Law; for instance, the bag and the jar activity from Lesson 5 and the stoppered flask in the three flasks activity from Lesson 7.

What happens when the variable of temperature is introduced into the equation? This lesson addresses Charles' Law. According to Charles' Law, in a closed system, an increase in temperature (T) results in an increase in volume (V); or a decrease in temperature (T) results in a decrease in volume (V) to maintain a constant pressure (P). In formulaic terms:

$$\frac{T}{V} = k \text{ where } k \text{ is some constant value and P is unchanging}$$

Taken together, Boyle's Law and Charles' Law completely describe the relationships between the pressure, temperature, and volume of a gas in a closed system. A "closed system" refers to a system that is not open to input or exchanges with the outside environment. (While no system can ever truly be closed, systems can be closed along certain parameters or to a certain extent. For instance, it is possible to construct a container that is air-tight so that it does not exchange gases with the outside environment, or to minimize temperature exchanges with the outside by insulating a container.)

Charles' Law and Relational Causality

A relational causal model nicely demonstrates the relationship that Charles' Law describes. Charles Law stipulates the relationship between temperature, volume and pressure. If temperature increases, then either the volume or the pressure (or some combination of the two) will increase. The opposite is also true. If temperature decreases, then either the volume or the pressure (or some combination of the two) will decrease. Pressure will only increase if the volume is held constant. In a flexible container, volume will increase (so pressure remains constant). In a closed and rigid container, volume stays constant and pressure increases instead. (This is in an ideal world with an ideal container. In the real world, there is some combination of change in pressure and change in volume to accommodate the temperature change.)

This makes sense from a molecular point of view: increasing the temperature of a gas causes the molecules to move faster, hitting the sides of the container or closed system more frequently and with more force. In order to maintain constant pressure, and knowing that pressure is defined as force per unit area (or $P = \frac{F}{A}$), the area that the gas is in contact with must increase as much as the force of the molecules hitting the container does. This results in an increase in volume. A flexible container, such as a balloon, illustrates this principle well. If the gas were kept in a rigid container with a fixed volume, an increase in temperature would result in an increase in pressure—more force from the molecules hitting the container, without any increase in area.

In this lesson, students do an activity that involves heating the air within a flask. This causes the molecules to move at a faster rate, hitting the sides of the container more frequently, which increases the force on the container walls. The volume of the gas increases, and a balloon on the flask inflates to maintain the air pressure inside the flask until it is at equilibrium with the outside air pressure. When the flask is removed from the heat source, the particles cool and slow down. This causes the balloon to deflate until the air pressure is again at equilibrium with the outside air pressure.

Lesson Plan

Materials

- Erlenmeyer flask, 250 ml, 1 per class
- Hot plate, 1 per class
- Tongs, 1 per class
- Balloon, 1 per class

Prep Step

- Review the lesson plan, background information, and understanding goals.
- Set out the hot plate and other materials.

Analyze Thinking

Step 1: Considering the Relationship Between Pressure and Temperature

Ask the students to think about what happens when molecules are heated. They should draw a picture illustrating what they think will happen.

If the molecules are heated while they are contained in a constant volume, what do students think will happen to the pressure? Will it stay the same, go down, or go up? Gather some ideas. What are they basing their predictions on?

RECAST Thinking

Step 2: Exploring the Relationship Between Heat and Volume When Pressure Remains Constant

Explain that the students will watch a demonstration that reveals information about the relationship between temperature and volume.

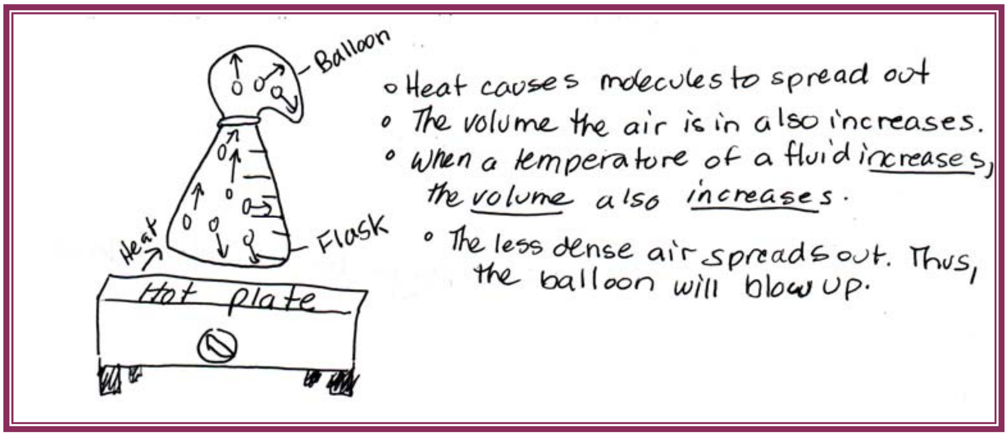
- Place a balloon over the opening of an empty flask and set the flask on the hot plate. Begin heating the flask.
- Tell students to predict what they think will happen by developing a model on paper or individual white boards.
- Ask several students to put their models on the board for the class to discuss. As they are doing this, have the class also observe what is happening to the balloon on the flask. (*As the air inside the flask is heated, the particles move around more quickly. This causes the air to expand within the balloon/flask system. Thus the balloon should inflate.*)
- As students watch, they should note whether their observations conflict with their predictions. If so, they should revise their models accordingly.
- Using tongs, place the flask onto a heat resistant counter to cool. As the flask cools, students should observe the balloon deflate.

Explore Causality

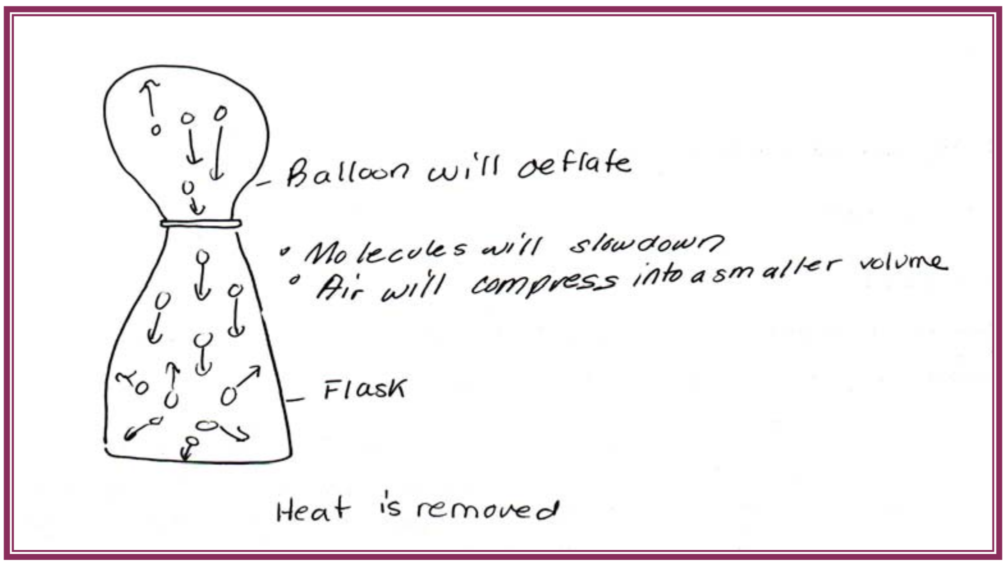
Step 3: Considering How Relational Causality Explains Charles' Law

- Ask the class to reflect on what they observed.
- Ask: "Is air pressure related to temperature? If so, how?" Remind students to think of obvious as well as non-obvious causes.
- Encourage students to draw a new model or revise their previous models. Have several students share their ideas and/or models with the class.

Examples of Students' Models



When the flask is heated



When the flask cools

- Ask: "Did you see any patterns in your observations? Did the air pressure change as the flask was heated?" (*No, that was why the balloon inflated or deflated…to maintain equilibrium.*)

Note to Teacher: Note whether any student mentions a relationship between the volume and the temperature. If they do not, ask them if they see any relationship between the two.

- Explain that scientists notice that volume and temperature are related, and they describe the relationship in a rule called Charles' Law.
- Charles' Law predicts that if the temperature of a fluid increases, the volume also increases (in a non-rigid container), thus pressure remains constant. In this activity, heating the air within the flask caused the molecules that make up the air to move at a faster rate. Thus they hit the sides of the container more frequently and the balloon inflated. When the flask was put onto the heat resistant counter, the molecules cooled, causing the balloon to deflate.
- Make sure that students understand that Charles' Law can be applied to most systems, however, in some systems, air pressure may not remain constant. (*Charles' Law can be used to predict what will happen to the volume of a fluid when the temperature is changed in order to maintain a constant pressure.)* This law only holds for 'closed systems', so make sure students understand this. *(A closed system is defined as a system where there is no exchange or interaction with the outside environment. Technically, no system is ever truly closed. Rather, systems are open or closed as a matter of degree and in terms of how we define the parameters that we are interested in controlling.)*

Review, Extend, Apply

Once the class understands the dynamics of what occurred within the flask, have them ponder whether the outside air pressure had any effect on what they observed. (*Students may note that before the balloon was placed on the flask, the pressure of the air inside the flask was the same as the pressure of the air outside the flask. When the air was heated inside the flask, its pressure increased, and in order for it to equilibrate with the outside air pressure, the balloon had to increase in volume…it inflated. When the flask was cooled, the air pressure inside the flask decreased until it was equal to the outside air pressure, and thus the balloon deflated.*)

Ask students to think about possible connections to what they just learned. For instance, what if they are riding their bicycles a long distance, or on a very hot day? If they checked their tire pressure, would they get the same reading before and after the long ride?

Note to Teacher: The reinforcement activity, *What Caused the Balloon to Get Pushed/Pulled Into the Flask?* (p. 128), offers a nice extension for this lesson.

Lesson 9
Relational Causality and Bernoulli's Principle

The following transfer lesson enables students to apply their understanding of pressure in a new context; specifically lift and Bernoulli's Principle.

Understanding Goals

Subject Matter

- ❖ The pressure in a fluid decreases as the speed of the fluid increases in a steady flow.
- ❖ Lift is possible because air has to travel further over curved surfaces than straight surfaces.

Causality

- ❖ A relational causal model can be used to understand lift and Bernoulli's Principle.

Background Information

Using Relational Causality to Explain Flight

Students have observed planes overhead, and many have traveled in them, yet most of them have little understanding of how a plane can fly. This is not surprising. It took centuries for humans to achieve flight. Daniel Bernoulli discovered in the 1700's that the pressure in a fluid decreases as the speed of the fluid increases in a steady flow. It follows that faster moving air exerts less pressure than slower moving air. Bernoulli's principle applies to fluids moving in a steady flow. However, if the flow speed is too fast, the flow can become turbulent and Bernoulli's principle no longer holds.

Air has to travel farther over curved surfaces than straight surfaces. Given a flat surface and a curved surface that connect the same two points, air traveling over the curved surface will go a longer distance than air traveling over the flat surface. In order to compensate for this longer distance, the air traveling over the curved surface must move faster. That is why airplane wings have curved surfaces on top and straight surfaces on the bottom. The faster moving air on the top exerts less pressure than the slower moving air on the bottom, and the wing moves up. This causes lift.

Causal Patterns in Air Pressure: Relational Causality

Lift is the net upward force that results from the differential between downward and upward pressures on the wing.

Bernoulli's Principle is Counter-intuitive

Bernoulli's principle is counter-intuitive for most people. The cognitive difficulties appear to relate to how people think about the wind. When we think of faster moving air, we tend to picture winds as they behave in a hurricane. When reasoning about wind, students often confuse what causes wind with the effects of wind. Winds are caused by air in areas of higher pressure moving towards areas of lower pressure. Pressure is omni-directional. However, the wind that results when air moves from areas of higher pressure to areas of lower pressure does have a direction, is forceful, and results in the push that we experience if we are in the path between the higher and lower areas of air pressure. Most students have strong experiential knowledge of the effects of the wind. They tend to carry clear images of the high-speed winds in hurricanes as forceful and powerful. Merely telling students that wind is caused by air moving from areas of higher and lower pressure and that pressure is not forceful, or that faster moving air exerts less pressure than slower moving air, will not convince them to see it differently. Engaging students in discussion to help them to see the role of pressure (in causing winds) and of force (as the effect of the direction of the wind) in the equation, and to differentiate between the two, will help them to see why the concepts are implausible to them. This, in turn, can help them to reason about Bernoulli's principle. When thinking about the lower pressure in faster moving air, encourage students to focus on the pressure exerted in all directions rather than the force exerted in the direction of the movement of the air.

As difficult as it is to understand, Bernoulli's principle is key to understanding many pressure-related events that occur everyday. These include weather phenomena such as hurricanes, tornadoes, and gales, as well as understanding car design, a curve-pitched baseball, and why the shower curtain often presses against your legs when you take a hot shower.

In this lesson, students will complete several activities to lead them to understand the effects of moving air on various-shaped surfaces. Lift will then be explored as a relational causal model, in that lift is made possible by the relationship or difference between the pressure on the upper and lower wing. Without this relationship, lift would not be possible.

Lesson Plan

Materials

One set of materials per student:
- Scrap paper
- Straw (optional)
- Tape
- 2"x 8 ½" strips of paper
- Scissors
- Ruler
- *Lift: Bernoulli's Principle* activity sheet, 1 per student
- *Mapping Out Relational Causality* sheets

Prep Step

- Review the lesson plan, background information, and understanding goals.
- Photocopy the activity sheets, *Lift: Bernoulli's Principle* (p. 117) and *Mapping Out Relational Causality in Lift* (p. 118).
- Photocopy the sheet, *The Causal Story of Lift* (p. 119).

Analyze Thinking

Step 1: Focusing on Current Thinking

Provide each student with a piece of paper and a *Lift: Bernoulli's Principle* activity sheet. Explain that they will be folding the paper in half like a tent and blowing under it. Ask what they think will happen. They should write their predictions on the activity sheet.

RECAST Thinking

Step 2: Experimenting With the Paper Tent

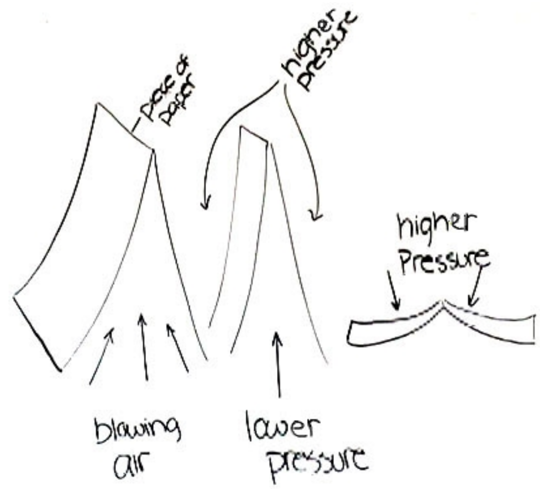
Have each student fold the piece of paper in half. Then have them place the paper like a tent on a smooth surface. Have them blow under it (they can use a straw if they wish). What happens? Have them test what happens multiple times.

Have the students draw a model to explain how the air moved through the paper to flatten it, and why they think this happened.

Bring the class back together to discuss what happened:

- Ask, "Was the result of your experiment what you had expected?" "Does the paper move toward or away from the fast-moving air?"
- Ask a few students to put their models on the board and to explain them.

- Discuss responses from the class, noting why the student predicted as he/she did in each case.
- Tell the class about Bernoulli and his principle. *Daniel Bernoulli, a famous scientist in the 1700's, studied fluids (anything that flows) such as air and water. He designed a principle to explain the effect of motion on fluid pressure. What Bernoulli found was that as the speed of a fluid increases, the pressure in the fluid decreases. So faster-moving air exerts less pressure than slower-moving air.*
- Ask, "How does this explain what is going on?" (*The paper gets flattened instead of blown away. Why? Because there is a difference in pressure. When you blew under the piece of paper, you made the air move faster, and decreased the air pressure. The air pressure on top was greater than the air pressure underneath. The paper was pushed toward the faster-moving, lower-pressure air.)*



Step 3: Discussing Whether Students Think That Bernoulli's Principle Makes Sense and is Plausible

Engage the students in a conversation about Bernoulli's principle. Try to find out if your students: 1) understand what it says, so that they know how to interpret it and; 2) find it to be believable.

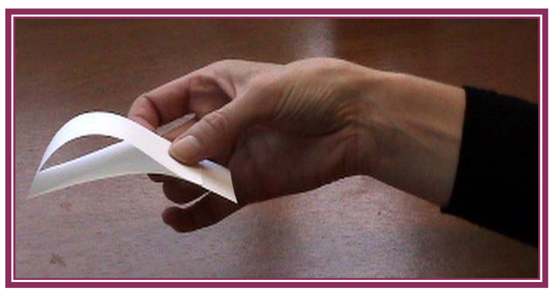
- Ask, "Do you understand what Bernoulli's principle says? Does it make sense to you?" Have some of the students explain it back to you using their own words. Probe students' conceptions and try to clear up any misunderstandings.
- Ask, "Do you believe what Bernoulli's principle says? Why or why not?" Gather arguments on both sides of the issue. If no one questions Bernoulli's principle, play devil's advocate and encourage them to grapple with the question of how faster moving air could exert less pressure. Encourage them to think about instances when they have experienced faster moving air (in a car, a windy day, hurricanes, and so forth). Does it seem to exert less pressure?
- Once students have recognized the discrepancy between their own experiences and what Bernoulli's principle predicts, ask if anyone can resolve the discrepancy. Gather students' ideas.

- Have the students step back from considering Bernoulli's principle and think about what causes the wind. Air is moving from areas of higher pressure to areas of lower pressure. Air pressure is omni-directional and exerts a push in all directions. However, the effect is wind, which moves quickly in a specific direction from areas of higher pressure to areas of lower pressure, and which is forceful in the direction in which it is moving. Through discussion and the use of models (student drawn and teacher drawn), help students to see the role of pressure (in causing winds) and of force (as the effect of the direction of the wind), and to differentiate between the two. Then come back to Bernoulli's principle. Encourage the students to see that the faster moving air pushes more forcefully in the direction that it is moving, but **not** in other directions. Here pressure is omni-directional and lower than slower moving air.

Step 4: Experimenting With Airplane Wings

What does Bernoulli's principle mean for flight? Provide each student with a 2" x 8½" strip of paper. Have each student:

- Fold the strip of paper in half. Tape one edge 1" from the other edge so that one side curves out.



- Insert a ruler and blow directly at the folded part. What happens? Does the paper wing move toward the flat part or the curved part?

- Experiment with different shaped wings. Try to make different amounts of curve in the wings.

Ask the class, “Why are airplane wings curved on the top? What would happen if they were curved on the bottom instead? Does the shape of the wing affect the way that it reacts to air pressure?” (*Air has to travel farther over curved surfaces than straight ones. The air traveling over the curved surface travels faster than the air moving over the straight surface. Therefore, the air moving over the top exerts less pressure than the air moving underneath the wing, so the wing moves up.)*

Have the students draw a model to explain how the air moved in relation to the wing. If you have time, you could have a student put their model on the board to discuss, or place your own on the board for the students to compare.

Explore Causality

Step 5: Reflecting on What Happened Using Relational Causality

Engage students in a discussion about how the paper tent and the airplane wing are similar. (*When students blew inside the paper tent, they noticed that the paper flattened. By increasing the speed of air, they decreased the pressure. Therefore, the paper moved towards faster moving air. This was similar to the airplane wing. It “lifted” towards the lower pressure.)*

Ask:

- “Can you explain, using relational causality, why the paper tent flattened? If so, how? If not, why not?”
- “In what way is using relational causality helpful in this context? What is difficult to understand, either in terms of pressure differentials or relational causality?”
- “Does this example of relational causality make sense? If so, why? If not, why not?”
- “Do other students seem to have similar understandings of relational causality in this case? How do other students' ideas compare to yours? How are they similar? How are they different?”
- “How does the use of relational causality compare to other examples you've thought about? That is, how is it similar to other examples? How is it different?”

Step 6: Thinking About the Causal Story of Lift

Pass out the sheet, *The Causal Story of Lift*. Read and discuss it together. Stress that in order to have lift, the pressure on the top of the wing must be lower than the pressure underneath the wing. One factor alone does not cause lift; it is caused by a relationship between the two pressures.

Step 7: Mapping the Relational Causality Involved

Have students complete the activity sheet, *Mapping Out Relational Causality in Lift*. Review the activity sheet with your students, making sure that they understand how relational causality is involved in lift.

Review, Extend, Apply

Step 8: Making Connections

Ask students to come up with other examples where Bernoulli's principle applies. They may not realize just how common it is. Try to generate a diverse list to offer a sense of its ubiquity. Discuss with the class which cases involve relational causality. Here are some examples:

- A fast-moving truck passes a car on the highway and the car is pulled towards the truck.
- When you turn on the water in the shower, the shower curtain immediately gets "sucked" into the shower and sticks to your legs.
- It is a very windy day. You push the front door closed with the same amount of force that you usually apply, and it slams much harder than you expect.

Resources for Section 3

Lesson 5

Modeling the Jar and the Bag Activity Sheet

Thinking About Relational Causality Sheet

Lesson 6

How Does a Syringe Work? Activity Sheet

Lesson 7

Drinking from a Straw: Models to Reveal What Happens Activity Sheet

Lesson 8

No Additional Resources

Lesson 9

Lift: Bernoulli's Principle Activity Sheet

Mapping Out Relational Causality in Lift Activity Sheet

The Causal Story of Lift Sheet

Modeling the Jar and the Bag

Name ______________________________ Date ________________

Purpose: To experiment with a pressure-related event and to develop the best model for explaining what happens.

Materials

- Two plastic sandwich bags
- One wide-mouthed glass jar
- A strong, thick rubber band

Part One:

1. Turn the bag upside down over the mouth of the jar and blow a little air into the bag so that it stays inflated over the jar.
2. Using the rubber band, seal the bag against the jar so that it is airtight.
3. Now try to push the bag into the jar (without tearing it).
4. Now answer the following question.

Why do you think the bag did what it did when you tried to push it in? In the space below, draw a model of what you think is going on. Label the parts of your model.

Explain your model above and <u>why</u> (you think) what happened occurred. Be sure to include both the "what" (your observations) and the "why" (your interpretations). Support your explanation by using evidence collected during your observations.

Part Two:

1. Disassemble the first bag from the jar. Place the second plastic bag inside the wide-mouthed jar and let the edge of the bag hang over the jar rim.
2. Seal it with the rubber band so that the bag is airtight against the jar. Try to take the bag out of the jar (without tearing it).
3. Now answer the questions below.

Why do you think the bag did what it did when you tried to pull it out? In the space below, draw a model of what you think is going on. Label the parts of your model.

Explain your model above and why (you think) what happened occurred. Be sure to include both the "what" (your observations) and the "why" (your interpretations). Support your explanation by using evidence collected during your observations.

Conclusions:

1. What similarities do you notice between your first and second models?

2. What differences do you notice between your first and second models?

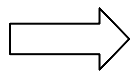
3. What are some possible non-obvious causes of what you observed?

Thinking About Relational Causality

We often analyze problems by using a *simple linear causality.* We say that one thing made another thing happen. One thing or event is the cause and it directly leads to one effect. For example, we might say, "the amount of air pressure in the balloon made the balloon soft."

Simple Linear Causality

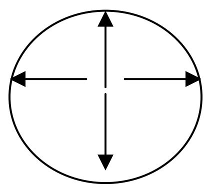
One variable, process, thing or event



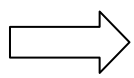
one outcome or effect.

causes

The amount of air pressure in the balloon



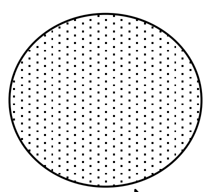
the balloon soft.



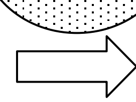
made

(This linear causal model uses arrows to show pressure in the balloon.)

The amount of air pressure in the balloon



the balloon soft.



made

(This linear causal model uses dots to show pressure in the balloon.)

However, scientists don't usually think about cause and effect in such a simple way. They use different forms of causality for different situations. When explaining air pressure, they often use a *relational causality.*

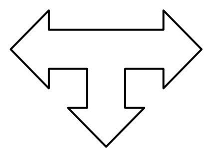
Here is a social example to help you see how a relational causality works:

> Two girls can be sisters, but neither girl alone is the "cause" of being sisters. It is the relationship between the two that "causes" them to be sisters. Comparisons can be made about the relationship. For example, you can say that one sister is older and one is younger, but it only makes sense in terms of the relationship, in comparing them to each other.

A relational causal explanation of the balloon sounds like this: For instance, the molecules that make up the air in the balloon are "pushing out" AND the molecules that make up the air outside the balloon are "pushing in." Scientists talk about it in terms of the relationship between the air pressure inside and outside. They compare areas of higher pressure and lower pressure. For example, a balloon appears squashed if the air pressure on the outside is higher and the air pressure on the inside is lower. The "cause" is not due to a low pressure inside the balloon or a high pressure outside the balloon, but the two taken together; the cause is due to the difference or relationship between the two pressures.

Relational Causality

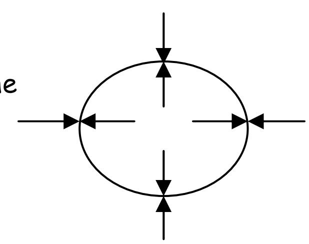
One variable, process, thing or event.



Another variable, process, thing or event.

Effect or Outcome

The air pressure inside the balloon "pushes out."

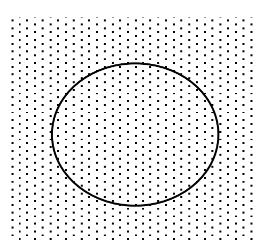


The air pressure outside the balloon "pushes inward."

The effect is that the balloon has a certain size and shape.

(This relational causal model uses arrows to show pressure in the balloon.)

The air pressure inside the balloon "pushes out."



The air pressure outside the balloon "pushes inward."

The effect is that the balloon has a certain size and shape.

(This relational causal model uses dots to show pressure in the balloon.)

In relational causality, the effect is caused by the relationship, and no single variable, process, event, or thing is the cause by itself. If you focus on only one part of the relationship, you lose important parts of the story.

How Does a Syringe Work?

Name ______________________________ Date ______________

Purpose: To experiment with the relationship between air pressure and volume as defined by Boyle's Law.

Materials

- One syringe

Directions

1. Place your thumb over the tip of the syringe. Envision what the air looks like inside the syringe and draw a model below:

2. Holding your finger over the tip, push the plunger down halfway. Draw what the air in the syringe looks like now.

3. Write a few sentences about what you think is happening in this situation in terms of air pressure.

4. Does your model above show what happens in terms of a relational causal model? If not, add to it, revise it, or draw a new model below.

5. Choose an instance from everyday life that illustrates Boyle's Law. Then, using relational causality, draw a model of what is going on in the instance you chose. Label your model and write a brief explanation of what happens below it.

Model:

Brief explanation:

Drinking from a Straw:
Models to Reveal What Happens

Name ______________________ Date ______________

1. Draw a model of what you think causes the liquid to rise in a straw when you drink from it.

2a. After someone in your group drinks from Flask B, draw a model to explain the cause of what you actually observed, even if it is similar to your previous model.

2b. Ask yourself, "Do my observations fit my model, or is there evidence that my model does not explain?" If so, list the unexplained evidence below.

3a. After someone in your group drinks the liquid from Flask C, draw a third model to explain the cause of what you actually observed, even if it is similar to your previous models.

3b. Ask yourself, "Do my observations fit my model, or is there evidence that my model does not explain?" If so, list the unexplained evidence below.

Go back to your initial model of what you think causes the liquid to rise in a straw when you drink from it. Has your thinking changed, or does your initial model still fit with your ideas? If your model has changed, revise your model below.

Lift: Bernoulli's Principle

Name ______________________________ Date ______________

1. What do you think is going to happen when you blow under the paper tent?

2. Why do you believe this will happen?

3. After you try the experiment, draw a model to explain how the air moved through and around the paper tent.

4. Draw a model of what happened in the paper airplane wing experiment.

Mapping Out Relational Causality in Lift

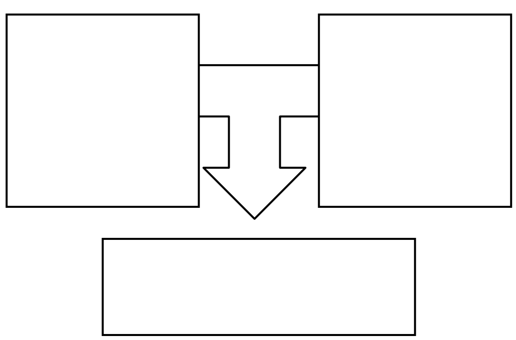
Name ______________________________ Date ________________

When thinking about how lift works, or how an airplane can fly, it is important to understand the effect of differences in air pressure on top of a wing and below a wing. Air moving across curved surfaces, such as the top part of a wing, moves faster than air moving across flat surfaces. Therefore, there is less pressure pressing down on the top part of the wing than on the bottom. In this way, the pressure on top of the wing and the pressure below the wing work together to cause lift (or to make the plane fly). Neither pressure alone is the "cause" of lift. It is the relationship between the two pressures that "causes" the plane to fly. It is useful to make comparisons about the relationship. For example, you can say that one area has lower pressure and one area has higher pressure, but it only makes sense in terms of the relationship, in comparing them to each other.

Map out how each event involves relational causality:

In relational causality, a relationship between two things (or variables) causes something to happen. (So it is more than just having two things, there needs to be a relationship between them.)

- In the top two boxes, write what the two things are.
- In the middle of the arrow, tell what the relationship is.
- In the bottom box, tell what the effect is.

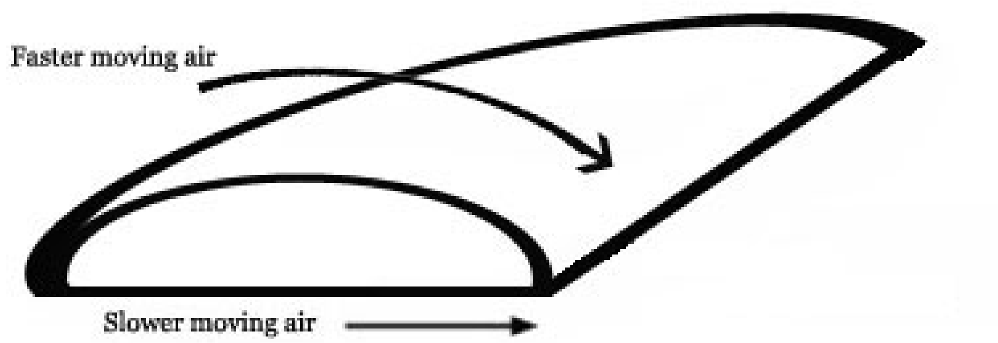


In relational causality, comparisons or differences between two variables are responsible for something happening or being so.

What comparison is responsible for the outcome of lift? In other words, how does the design of an airplane help it fly?

The Causal Story of Lift

Lift is best described by a relational causal story. Lift is due to the difference in air pressure between the top and the bottom of an airplane wing. Airplane wings are curved, as pictured below, so when they move through the air, the air along the top has farther to travel to get to the other side than the air moving across the flat surface on the bottom. Therefore, it must move more quickly. Air exerts pressure on everything, but faster moving air exerts less pressure that slower moving air. This is Bernoulli's principle. Therefore, the cause of lift is the relationship between the speed of the air on the top and bottom of the wing.



Cross section (slice) of airplane wing

If the air pressure on the top and the bottom of the wing are equal, then the air pushes equally on the top and the bottom of the wing and there is no lift. If the air pushes more on the bottom than on the top, it enables the wing to lift up. What do you think would happen if the curved piece were on the bottom of the wing? The outcome depends upon the relationship of the air pressure on the top to the air pressure on the bottom, so you need to look for the cause of the outcome in the relationship between the two.

Reinforcement Activities

A Microscopic View of Boyle's Law Using "Atomic Microscope 3-D"—(p. 122) This computer simulation enables students to get a 'microscopic' view of what is happening within the syringe as you increase or decrease the volume. This demonstration can be found at: http://www.starkdesign.com/ . Alternatively, teachers could use: *Virtual Molecular Dynamics Laboratory*, free from the Boston University Center for Polymer Studies http://polymer.bu.edu/vmdl/ .

The Balloon and the Bell Jar (p. 123)—This activity underscores how a balloon's shape and size is a result of the balance of pressure between the inside and the outside of the balloon, and highlights the importance of using a relational causal model to interpret what happens.

Revisiting Water in a Straw (p. 125)—Why can you put your finger on the end of a straw when it is in water and lift it out, and have the water stay in the straw? Students explore this question using Boyle's Law to expand upon their reasoning from Section 2.

What Causes the Balloon to Get Pushed/Pulled Into the Flask? (p. 126)—Students see a balloon get pushed/pulled into a flask as it cools. Using Charles' Law and relational causality, they can reason out what happened to realize that the pressure inside the flask is lower than the pressure outside of the flask, and that this pressure differential results in the balloon getting pushed into the flask.

Can Air Crush a Soda Can? (p. 129)—In this activity, water is boiled inside a can so that the volume of the air and water vapor expands to fill the inside of the can. The can is then quickly inverted in a tub of cold water and the cooling of the inside air results in an air pressure differential between the inside and outside of the can. As a result, the can is crushed. This is a dramatic example of relational causality.

Making Connections Using Relational Causality (p. 130)—This activity is designed to help students transfer what they have learned about relational causality to a new set of questions. The sheet asks each student to choose two questions that interest him or her and to map them out as students have mapped out the relational causality for the activities in the lessons (the three flasks, balloon and flask, lift, and so on). The activity sheet is self-explanatory (once students have mapped the instances in the activities).

Mapping Relational Causality (p. 132)—This activity is designed to help students map out the variables in relational causality. It can be used with any example, particularly those from the lessons (the three flasks, balloon and flask, or paper tent, for instance).

Transferring Relational Causality (p. 134)—This activity sheet is designed to help students transfer relational causality. It starts with a balloon example and gives transfer examples for students to map out.

Charles' Law and the Rising Water (p. 138)**—**When a glass is placed over a burning candle in a plate of water, the water level rises significantly when the candle burns out. Using Charles' Law and relational causality, students realize that the combination of the quick decrease in the temperature of the air in the glass when the candle burns out and the condensation of the water vapor results in lower air pressure in the glass than outside the glass. Although it is difficult to tease apart which one of these variables has the more significant impact, both result in a lower air pressure inside the glass, which leads to the rising water in the glass.

A Microscopic View of Boyle's Law Using *Atomic Microscope 3-D*

(Reinforcement Activity)

Get a computer and TV projection monitor and show *Atomic Microscope 3-D,* a computer simulation of Boyle's Law (www.starkdesign.com). This simulation enables students to get a 'microscopic' view of what is happening within the syringe as you increase or decrease the volume. Alternatively, you can use *Virtual Molecular Dynamics Laboratory* free from the Boston University Center for Polymer Studies, http://polymer.bu.edu/vmdl/ .

- Note that the amount of air within the container does not change when the volume is increased or decreased, as some of students may have predicted would happen with the syringe.
- Have the class consider what is limiting about this model of air pressure. Hopefully some students will note that the designers only focused on the air pressure within the container and did not model the outside air pressure. Thus it is a linear model.

The Balloon and the Bell Jar

(Reinforcement Activity)

Materials

- Large bell jar with solid base to which a “pressure pump” can be attached
- “Pressure pump” (more commonly known as “vacuum pump”) or some device that can remove the air from the jar
- Two partially inflated balloons (same size)
- Petroleum jelly to use as a sealant between the jar and the base
- Masking tape

Background Information

This activity underscores how a balloon's shape and size are a result of a balance of pressure between the inside and the outside of the balloon, and highlights the importance of using a relational causal model to interpret what happens. To make the relationship obvious, we place the balloon in a bell jar. Using a pressure pump, we reduce the pressure of the air in the jar and observe the effects it has on the balloon. The balloon will expand due to the air pressure differential between the inside and the outside of the balloon. Then the situation is switched. The air pressure is increased, and the balloon deflates. This demonstration makes the relational causality obvious, and leads many students to revise their initial models of what gives a balloon its shape and size.

Steps

1. Present an inflated balloon to the class and ask, “What gives a balloon its shape and size? Think about this for a moment and then draw your ideas on paper.” After several minutes, ask students to share their ideas with the class. *Presumably students will give unidirectional/linear models that focus on the air and/or pressure inside the balloon. Do not attempt to address these models yet.*
2. Tape the balloon to the top of a bell jar and place the jar on a solid base. Be sure to apply a generous amount of petroleum jelly to the bottom of the bell jar before placing it on the solid base to create the most efficient seal possible. Ask the students to note whether or not this set-up affects the balloon.
3. Place the second balloon by the side of the jar for comparison. Then reduce the air pressure inside the jar by attaching the pressure pump to the base of the set up and turning it on. Have the students observe what happens. *As the air inside the jar is removed, the balloon expands due to the differential in air pressure.*
4. Have students draw a model on a piece of paper or individual white boards.

5. Ask the students to watch as you increase the air pressure in the jar. What do they think will happen? Gather ideas from the class. *Adding air to the jar with the pressure pump results in the balloon imploding, due to the differential in air pressure between the lower air pressure inside the balloon and the higher air pressure in the jar.*
6. Have students draw a model. Invite students to also modify their earlier models if the results inspire them. Have students share and critique their models of what happened. Note which models account for the relational causality involved in the experiment.

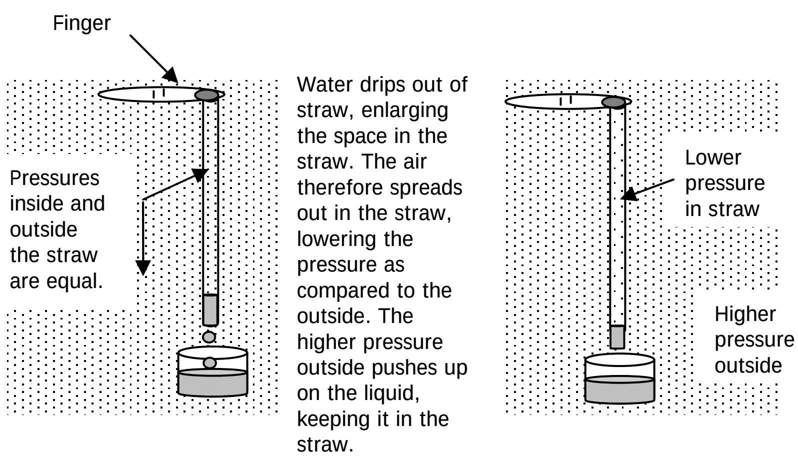
Revisiting Water in a Straw

(Reinforcement Activity)

Present the following question for your students to consider: “You are able to keep the water in a straw by placing your finger over the top of the straw and taking it out of the cup. Thinking about this in terms of air pressure, can you explain this phenomenon?” Have students draw a model.

By closing off the top end of the straw with our forefinger, we prevent more air from coming in. Some water will drip out of the lower end of the straw, enlarging the volume of the air pocket above the water and thus creating a lower air pressure inside the straw. This is essentially an example of Boyle’s law. If you increase the volume of the enclosed air, the air pressure decreases. The outside air pressure remains the same. This difference in air pressure means that a greater number of the molecules that make up the air are bouncing off the water at the bottom of the straw than at the top, so the water remains in the straw. When the finger is released, there is no longer a difference between the air pressure of the inside and outside of the straw, thus the fluid flows out of the straw.

Model:



Before After

What Causes the Balloon to Get Pushed/Pulled Into the Flask?[2]

(Reinforcement Activity)

Materials

- Hot plate
- Erlenmeyer flask, 250 ml with 20 ml of water in it
- Balloon
- Tongs
- *What Causes the Balloon to Get Pushed/Pulled into the Flask?* activity sheet

Background Information

In this activity, a balloon and flask are heated as in Lesson 8. However, this time a small amount of water is placed in the flask and brought to a boil first. As it is heated the molecules in the air and the water speed up and spread out, taking up more space. Then the balloon is put on the flask, making it a closed system. When the balloon and flask cool, additional molecules cannot enter the flask to take up the additional space as the molecules in the container slow down and the water vapor condenses. Therefore, the pressure inside the flask is lower than the pressure outside of the flask. This pressure differential results in the balloon getting pushed into the flask. *It is not the case that the outside air pressure alone pushes the balloon into the flask; it's an imbalance in the relational model that results in the air pressure pushing the balloon into the flask.*

Steps

1. Place about 20 ml of water in the flask and boil it before you put a balloon on the top, as in Lesson 8. Then remove the flask/balloon set-up and let it cool. As it cools, have students observe what happens. (*The balloon should get 'pushed' into the flask.*)
2. Working in groups of three, have students discuss what is going on and try to come up with a model to explain their observations. Pass out the activity sheet, *What Causes the Balloon to Get Pushed/Pulled into the Flask?* to guide them. While they are thinking, invite them to come up and observe the balloon in the flask.
3. Bring the class back together for a discussion. Gather ideas. Have two or three students put their models on the board. (Try to get a variety of models). See if others agree or disagree and why. Note similarities in all of the models and list these on the board. How does a relational causal model give the best explanation for what happens? (*As the air inside the flask cooled, the heated molecules slowed down and the water vapor condensed on the inside of the flask. This created a lower air pressure than what there was initially. This air pressure differential—lower inside, higher outside—resulted in the balloon*

not only deflating, but being <u>*pushed*</u> *into the flask until equilibrium was reached.)* Emphasize how the term “pushed” rather than “pulled” more accurately describes what happened to the balloon. Be sure that students know that movement is from higher to lower pressure, so that it appears that lower pressure pulls matter from areas of higher pressure towards it, and higher pressure pushes matter towards areas of lower pressure.

What Causes the Balloon to Get Pushed/Pulled Into the Flask?

(Reinforcement Activity)

Name ______________________________ Date ______________

We have been learning about Charles' Law. According to Charles' Law, as the air inside the balloon and flask cools, its volume should decrease until the air pressure inside the flask is equal to the air pressure outside the flask. But the balloon did not return to its original position. Instead it got pushed/pulled into the flask! Why did this happen?

Use what you've learned about obvious and non-obvious causes and relational causality to come up with a model to explain this demonstration. Think about all of the possible variables involved, and how they relate to each other.

Ask yourself, "Was the balloon pulled into the flask or pushed into the flask?" Reasoning with relational causality can help you figure this out.

Draw your model:

Explain your model:

Review: Read your explanation and analyze your model carefully. List any 'gaps' in your model and explanation that you cannot account for:

Can Air Crush a Soda Can?
(Reinforcement Activity)

Materials

- Aluminum soda can
- Tub of cold water
- Hot plate or other heat source
- Tongs
- Oven mitt

Steps

1. Have students watch as you heat approximately one inch of water in the bottom of a soda can (holding the can with a set of tongs). After the water has boiled for about 30 seconds, remove the can from the heat, immediately inverting it into a tub of cold water. The students will see that the can is immediately crushed.
2. Gather ideas. Help the students connect what they learned in this section to what they have just observed.
3. Ask the students to think about what crushed the can. Remind them to think about non-obvious causes and relational causality. How are each involved here?
4. Ask the students to reflect on the following question: “We said that air pressure behaved passively, but that it was noticeable in certain instances. What is going on here that makes it so noticeable?”

Making Connections Using Relational Causality
(Reinforcement Activity)

Name ________________________________ Date ________________

Choose two of the questions below. Analyze the situations using a relational causal model. Draw a diagram illustrating your thinking and write a 5-10 sentence explanation.

- Why does a dam need to be so strong?
- Why does a balloon pop if you push hard enough on the outside?
- Why do helium balloons often pop when they reach great heights?
- Why can't a freshwater fish survive in salt water?
- Why do mountain climbers need to wear oxygen tanks when climbing to great heights?
- When someone dives to very great depths without wearing scuba gear, why is it possible for their lungs to collapse?

Question #1 ____

Draw your relational model here:

Write your explanation here:

Question #2: ____

Draw your relational model here:

Write your explanation here:

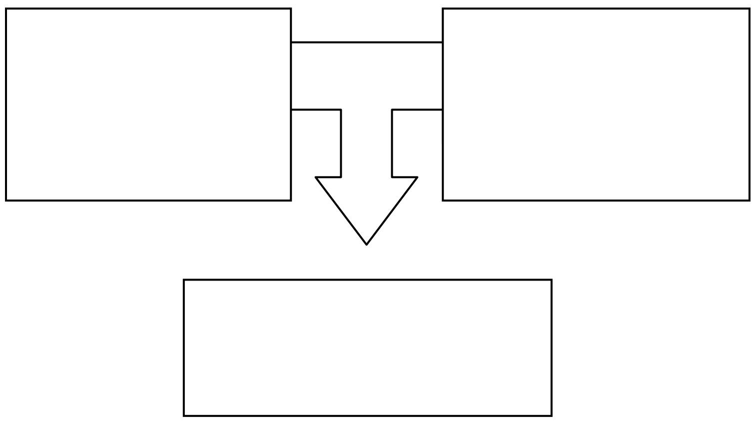
Mapping Relational Causality

(Reinforcement Activity)

Name ________________________________ Date ___________

1. In relational causality a relationship between two things or variables causes something to happen. (So it is more than just having two things, there needs to be a relationship between them.)

   - In the top two boxes, write what the two things are.
   - In the middle of the arrow, tell what the relationship is.
   - In the bottom box, tell what the effect is.



2. In relational causality the relative amounts of two things are equal or different, and that tells you the outcome. (For example, one is younger/older, more/less, higher/lower etc. than the other.)

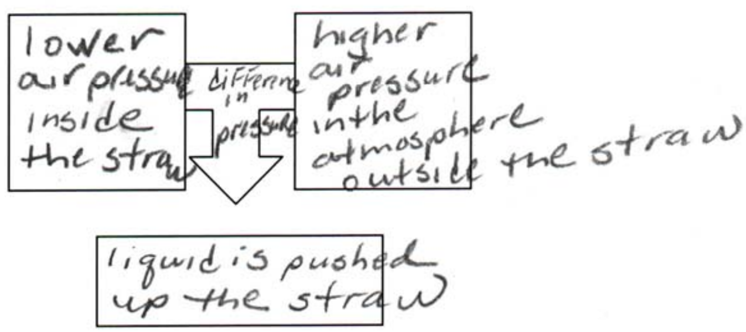
   When figuring out what type of causality is involved, think about the following questions/issues:

   - Must the two things work in <u>relationship to one another</u> to make the effect happen?
   - If one of the two things changes (so that the relationship changes), does the outcome change?
   - Can a comparison be made between the amounts of the things?
   - If one cause can result in the effect without the other cause, then it is not relational causality.
   - If you have two causes, but there is no comparison between them, (you just add them up or do first one and then the other), then it is not relational causality.

Mapping Relational Causality
(Reinforcement Activity)

Name Shana

1. In relational causality a relationship between two things or variables causes something to happen. (So it is more than just having two things, there needs to be a relationship between them.)
   - In the top two boxes, write what the two things are.
   - In the middle of the arrow, tell what the relationship is.
   - In the bottom box, tell what the effect is.



2. In relational causality the relative amounts of two things are equal or different, and that tells you the outcome. (For example, one is younger/older, more/less, higher/lower etc. than the other.)

   When figuring out what type of causality is involved, think about the following questions/issues:
   - Must the two things work in <u>relationship to one another</u> to make the effect happen?
   - If one of the two things changes (so that the relationship changes), does the outcome change?
   - Can a comparison be made between the amounts of the things?
   - If one cause can result in the effect without the other cause, then it is not relational causality.
   - If you have two causes, but there is no comparison between them, (you just add them up or do the first one and then the other), then it is not relational causality.

Note to Teacher: Here is an example of a student's response mapping the relational causality involved in explaining what happens when you drink from a straw.

Transferring Relational Causality

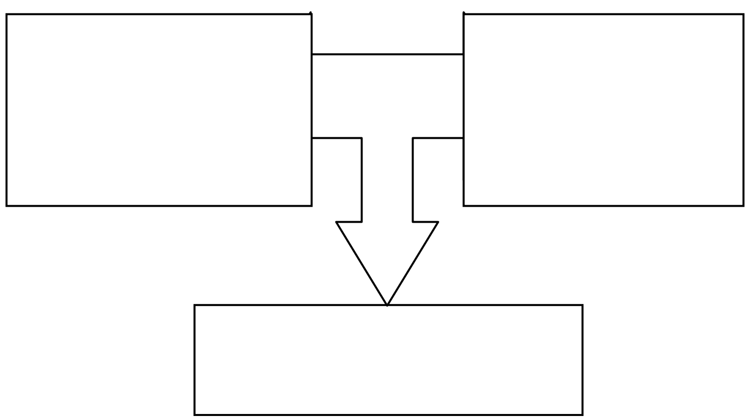
(Reinforcement Activity)

Name________________________________ Date ____________

A balloon gets its size as a result of air pressure inside the balloon and air pressure outside the balloon, but neither air pressure is the “cause” of the balloon's size. It is the relationship between the two pressures that “cause” the balloon to be bigger or smaller. (Of course, if there is too much pressure inside for the size of the balloon it will pop!) You can make comparisons about the relationship. For example, you can say that a balloon is smaller because there is more air pressure "pushing" against it from the outside compared to the pressure inside the balloon that "pushes" outward. It only makes sense in terms of the relationship when you compare the two pressures to each other.

In relational causality, a relationship between two things or variables causes something to happen. (So it is more than just having two things, there needs to be a relationship between them.) Fill in the blocks below to explain how a balloon gets its shape.

- In the top two boxes, write what the two things are.
- In the middle of the arrow, tell what the relationship is.
- In the bottom box, tell what the effect is.



In relational causality comparisons or differences between the two things are responsible for something happening or being so.

Choose 2 of the 6 questions below to explain the questions on the following pages:

- Why does a dam need to be so strong?
- Why does a balloon pop if you push hard enough on the outside?
- Why do helium balloons often pop when they reach great heights?
- Why can't a freshwater fish survive in salt water?
- Why do mountain climbers need to wear oxygen tanks when climbing to great heights?
- When someone dives to very great depths without wearing scuba gear, why is it possible for their lungs to collapse?

For the 2 questions you choose to explain:

a. Write out the full question on the lines provided.
b. Draw a relational model illustrating your ideas.
c. Map out the relational causality in the boxes. Then explain your model and ideas in the space provided.

a. Question #1: ____

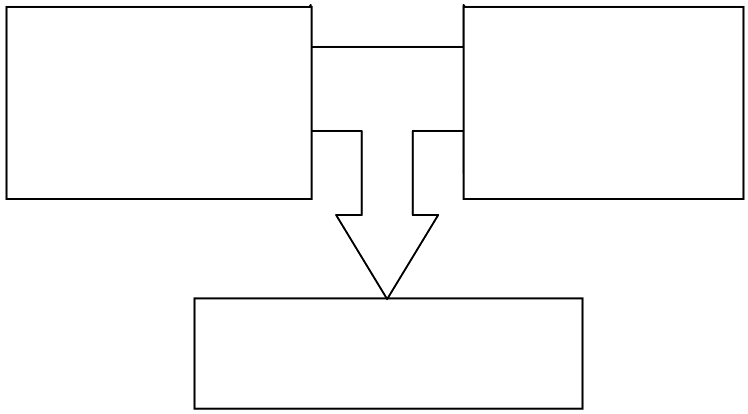
____

b. Draw a model illustrating your idea

c. Map out the relational causality in the boxes

In relational causality, a relationship between two things causes something to happen. (So it is more than just having two things, there needs to be a relationship between them.)

- In the top two boxes, write what the two things are for your question.
- In the middle of the arrow, tell what the relationship is.
- In the bottom box, tell what the effect is.



In relational causality, comparisons or differences between the two things are responsible for something happening or being so.

Write your explanation here:

a. Question #2: ____

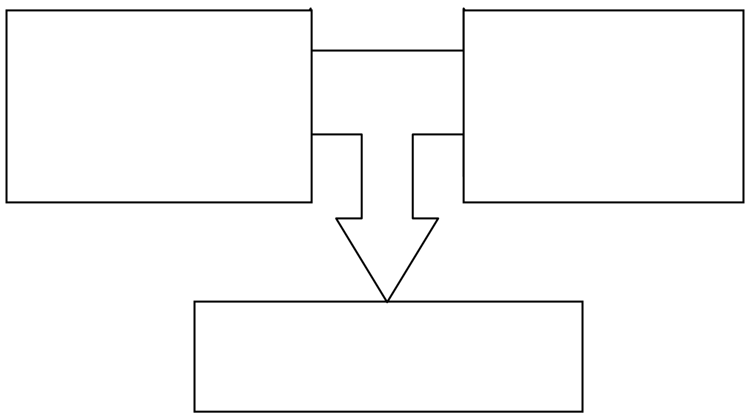
____

b. Draw a model illustrating your idea:

c. Map out the relational causality in the boxes

In relational causality, a relationship between two things causes something to happen. (So it is more than just having two things, there needs to be a relationship between them.)

- In the top two boxes, write what the two things are.
- In the middle of the arrow, tell what the relationship is.
- In the bottom box, tell what the effect is.



In relational causality, comparisons or differences between the two things are responsible for something happening or being so.

c. Write your explanation here:

Charles' Law and the Rising Water Activity[3]

(Reinforcement Activity)

Materials

One set of materials per group of 3 students:

- Tall glass
- 25 ml water
- Birthday candle
- Small ball of clay
- Match
- Flat plastic dish
- *What Causes the Water to Rise in the Glass?* (p. 141) activity sheet

Background Information

When a glass is placed over a burning candle in a plate of water, the water level rises significantly when the candle burns out. This is due to a combination of factors. First, the burning candle significantly increases the temperature of the air in the glass. When the candle burns out, the rapid decrease in temperature slows the movement of the molecules that make up the air inside the glass, creating lower pressure. The air pressure outside of the glass remains the same. This creates an air pressure differential of greater outside air pressure, which results in the water rising in the glass. In addition, going from a higher temperature to a lower temperature causes water vapor in the air to condense, which also produces lower air pressure in the glass. Although it is difficult to tease apart which one of these variables has the more significant impact, both result in rising water in the glass.

Steps

1. Pass out *What Causes the Water to Rise in the Glass?* activity sheet to each student.
2. Have students work in groups of three.
3. Go through the procedure for setting up the activity so students are clear about what to do. In the activity, students try to determine what causes the liquid to rise in a glass that contains a burning candle under it. Emphasize that they are doing the work in small groups so that they can closely observe what happens. *They should observe that the water rises significantly once the candle goes out.* Have them complete the activity using the sheet to guide them. They may not complete it in one day.
4. If they need more time, pick a good place to stop. (For instance, they could run the experiment once before the end of class and think about it for homework.)
5. Have three or four students put their models on the board and explain them to

the class. Try to get one model that focuses on the candle burning, with oxygen being used up as the cause of the water rising. Note to the class that this is a non-obvious cause.

6. Look for similarities in the models and list them on the board next to the similarities noted in the balloon/flask activity. Ask, “Are these the same?” (*Hopefully students will notice the moisture in both*.) Ask, “What about the models are not similar? Can anyone think of a way we can test some of these models?”

If a model of burning oxygen is on the board (see resource sheet on p. 143 for explanation):

7. Do the activity again, but this time, have students note **<u>when</u>** the water rises the most. They should note that it does so once the flame has gone out. Does this fit the burning oxygen model? (*No*. *If that were the cause, then the water would rise as the oxygen was used up, but that does not fit their observations*.)
8. What else could be going on? Elicit ideas from the class.
9. If students still are not convinced that the “oxygen being used up” model does not fit, have them predict what would happen if they added more candles to their system. If the oxygen model is correct, the water should eventually rise to the same level no matter how many candles are added, since there is a fixed amount of oxygen in the glass. They should see that the more candles they add, the higher the water rises in the glass. Have them think of why this may be so.

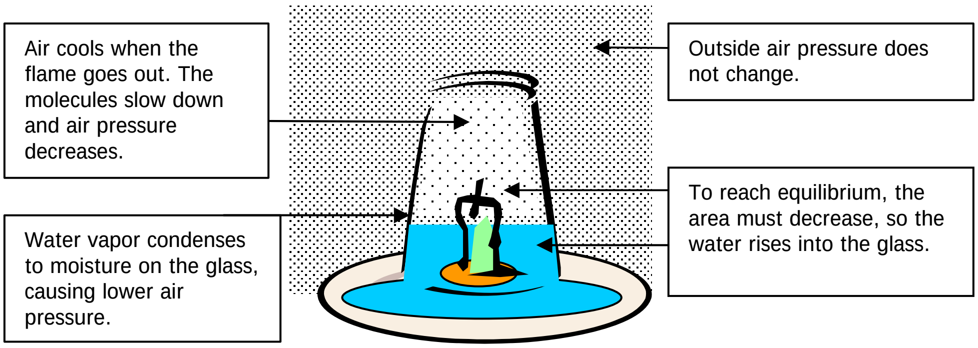
If a temperature model is not on the board (see resource sheet on p. 143 for explanation):

10. Do the activity again, but this time, have students think about it in terms of temperature. *There are two explanations related to temperature. First, the lower temperature created when the candles go out causes lower air pressure, so the outside air pressure is greater (most students don’t note this unless you specifically mention it to them). The outside air pressure pushes more on the water than the inside pressure, so the water is then pulled up into the glass until equilibrium is reached. Second, when you add more candles, the air becomes proportionally hotter, and the rapid temperature change (from high to low) when the candle goes out causes water vapor inside the glass to condense on its sides. This creates lower air pressure inside the glass, so the outside air pressure pushes more on the water than the inside pressure. This causes the water to rise in the glass until equilibrium is reached.*

If a vacuum model is on the board (see resource sheet on p. 144 for explanation):

11. Tell the class, “People often say ‘Nature abhors a vacuum.’ Why do you think people say this?” Gather responses. “If a true vacuum were created, what would you observe?” (*The glass would implode.*)

What actually happens?



The evaporation of the water to water vapor as the candle burns, and the cooling that occurs when the candle goes out, cause lower air pressure inside the glass than outside. The water is pushed into the glass until equilibrium is reached.)

Demonstration of Rising Water Activity

What Causes the Water to Rise in the Glass?
(Reinforcement Activity)

Name_________________________________ Date____________

How can you use what you've learned about obvious and non-obvious causes and relational causality to come up with a model to explain why the water rises in the glass? Think about all of the possible variables involved and how they relate to each other.

Materials

- Tall glass
- Birthday candle
- Matches
- Water
- Flat dish
- Small ball of clay

Directions

1. Stick the bottom of a candle into a ball of clay. Press the ball of clay into the center of the dish. The candle should be standing straight up in the center of the dish.
2. Fill the glass half full with water and pour the water into the shallow dish.
3. Light the candle, invert the glass over the candle and set the glass mouth down into the water. (See figure above.) Carefully observe what happens.
4. You may have to repeat the procedure several times.
5. Write an explanation and draw a model to explain what caused the water to rise in the glass.

Draw your model here:

Write your explanation here:

Examples of Student Models:
'What Causes the Water to Rise in the Glass?'*

Burning Oxygen Model

This is the most common model that students use when explaining why the water rose in the glass. In this model, students reason that as the candle burned, it "used up" the oxygen that was trapped under the glass. The water rose because the candle "used up" all of the oxygen that was in the air. Students often fail to explain how the lack of oxygen in the air caused the water to rise in the glass. Rather, they focus on the most obvious aspect of the experiment, the candle going out, and attribute that as the cause of the water rising. Although the cause of the candle going out was a lack of oxygen, it was not the cause of the water rising in the glass. To have students question this model, do the activity again, but this time have students note **when** the water rises the most. They should note that it does so once the flame has gone out. Does this fit the burning oxygen model? No. If that were the cause, then the water would rise as the oxygen was being used up, and would stop rising when the candle went out, but that does not fit the evidence. If students still are not convinced that the "oxygen being used up" model does not fit, have them predict what would happen if they added candles to their system. If the oxygen model is correct, the water should rise to the same level no matter how many candles are added, since there is a fixed amount of oxygen in the glass. However, they should see that the more candles they add, the higher the water rises in the glass, evidence that is not supported by the oxygen model.

Temperature Model

Most students focus on the burning of the candle. Few make the connection between the burning candle and a subsequent rise in the temperature of the air trapped under the glass. There are two possible explanations for how temperature results in the water rising in the glass that students may mention. First, the lower temperature created when the candle goes out causes lower air pressure (the molecules that make up the air slow down). The outside air pressure is greater (most kids don't note this unless you specifically mention it to them) so the outside air pressure pushes on the water to a greater extent than the inside air pressure, and the water is pulled up into the glass until equilibrium is reached. Second, when you add more candles, the air becomes proportionally hotter, and the rapid temperature change (from high to low) when the candle goes out causes water vapor inside the glass to condense on its sides. This creates lower air pressure inside the glass, so the outside air pressure pushes more on the water than the inside air pressure. This causes the water to rise in the glass until equilibrium is reached.

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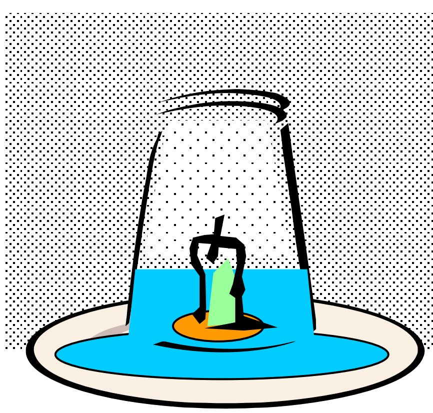
* These ideas and models were generated by a group of teachers during a summer workshop.

Vacuum Model

Some students might mention that a vacuum is created inside the glass by the burning candle, which sucks the water up. To address this model, tell the class that people often say, “Nature abhors a vacuum.” Ask: “Why do you think people say this?” Gather students' ideas. Then, have them think deeply about what we would observe if a true vacuum were created inside the glass. That would mean that there was no air whatsoever in the glass. If that were the case, the higher outside air pressure would immediately implode the glass. Since this does not occur, students should conclude that a vacuum was not the cause of the water rising in the glass. However, you might find that some of your students still hold on to the idea of a “partial vacuum.” Ask them to explain what they mean by a “partial vacuum.” It might be the case that their ideas are those of a lower air pressure, but they are using the token agent of a partial vacuum, since this terminology might be more familiar to them.

Air Pressure Differential Model

The cause of the water rising in the glass can actually be attributed to several variables that result in the creation of an air pressure differential between the inside and the outside of the glass. As the candle burns, the temperature of the air inside the glass increases rapidly. This temperature increase also results in additional water vapor in the air. When the flame uses up all of the oxygen in the glass, the candle goes out. This causes the air to cool rapidly, and causes condensation to form on the inside of the glass. Both of these variables create an area of lower air pressure inside the glass as compared to the higher air pressure outside the glass. This results in the outside air pushing on the water, which causes it to rise in the glass until the two air pressures reach equilibrium.



Endnotes for Section 3

[1] Hogan, K (1999, April). *Collective Metacognition: The Interplay of Individual, Social, and Collective Meanings In Small Groups' Reflective Thinking*. Paper presented at the American Educational Research Association, Montreal.

[2] Liem, Tik, I. (1992). *Invitations to Science Inquiry*. Chino Hills, CA: Science Inquiry Enterprises.

[3] Adapted from Liem, Tik, I. (1992).