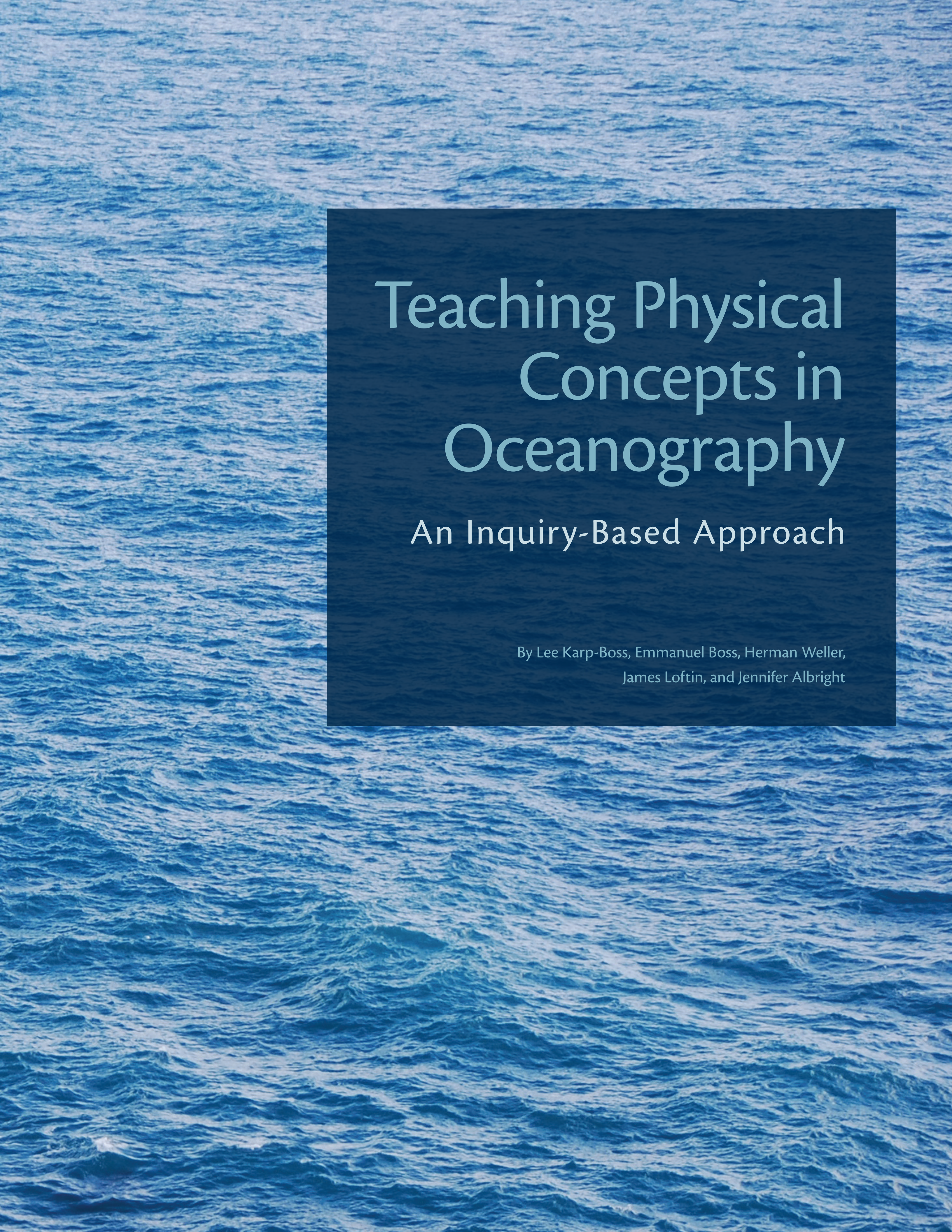

# Teaching Physical Concepts in Oceanography

## An Inquiry-Based Approach

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# INTRODUCTION

This supplement to *Oceanography* magazine focuses on educational approaches to help engage students in learning and offers a collection of hands-on/minds-on activities for teaching physical concepts that are fundamental in oceanography. These key concepts include *density*, *pressure*, *buoyancy*, *heat and temperature,* and *gravity waves*. We focus on physical concepts for two reasons. First, students whose attraction to marine science stems from an interest in ocean organisms are typically unaware that physics is fundamental to understanding how the ocean, and all the organisms that inhabit it, function. Second, existing marine education and outreach programs tend to emphasize the biological aspects of marine sciences. While many K–12 activities focus on marine biology, comparatively few have been developed for teaching about the physical and chemical aspects of the marine environment (e.g., Ford and Smith, 2000). The ocean provides an exciting context for science education in general and physics in particular. Using the ocean as a platform to which specific physical concepts can be related helps to provide the environmental relevance that science students are often seeking.

The activities described in this supplement were developed as part of a Centers for Ocean Sciences Education Excellence (COSEE) collaboration between scientists and education specialists, and they were implemented in two undergraduate courses that targeted sophomores, juniors, and seniors (one for marine science majors and one including both science and education majors) and in four, week-long workshops for middle- and high-school science teachers. Below, we summarize our educational approach and discuss the organization of this volume.

## VERIFICATION OR DISCOVERY?

Our approach to teaching science has its basis in three important "discoveries" we made. We put *discoveries* in quotation marks because many people discovered them before us. However, until we "discovered" them ourselves, we did not realize their significance. This process is similar to the experiences of our students, who discover for themselves how physics can help explain the environment in which they live.

*Our first realization was that our usual way of teaching science at the university level, through delivery and recitation of textbook material, resulted in the transfer of science facts but did not reflect the way science is done.* In our usual approach, students were typically passive observers with very little engagement or use of inquiry. Science, however, is not only about "bodies of knowledge"; science is a way of thinking and doing, where inquiry is an inherent process. When we "do" science, we make predictions, generate questions and falsifiable hypotheses, take measurements, make generalizations, and test concepts by application. According to the National Science Education Standards (National Research Council, 1996), "In the same way that scientists develop their knowledge and understanding as they seek answers to questions about the natural world, students develop an understanding of the natural world when they are actively engaged in scientific inquiry—alone and with others." Students do not engage in inquiry when they are taught *about* the products of science (e.g., facts, concepts, principles, laws, and theories) and the techniques used by scientists. In our usual way of teaching science, labs were often used for science verification. In that mode, the laws of physics were first introduced and the lab was then used to illustrate them. Emphasis was on data collection, plotting, and the writing of reports. Such exercises most often lacked the element of exploration.

We have come to understand that *inquiry* and *exploration* are essential to exciting students' curiosity and interest in science. Outliers in experimental data are often more interesting than the points that fit theory, as they require an explanation beyond the material available in textbooks. The explorative approach can provide students with a deeper understanding of the scientific process and can help develop critical thinking skills—skills that are rarely called for in the verification approach.

*Our second realization was that a student's ability to recite textbook content and formulas does not necessarily indicate an understanding of the underlying physical principles.* Physics can be taught using mathematical descriptions. Students can learn which equations will yield which quantities, and this knowledge can be readily assessed in written exams. However, this approach does not necessarily develop a student's ability to recognize when fundamental principles might be applied to slightly different problems. We "discovered" that our students achieved deeper learning and a more profound understanding of physical concepts when they took an active part in learning—for example, when they performed hands-on experiments that gave them an opportunity to "see/feel" for themselves what the mathematical descriptions model.

## CREATING MEANINGFUL LEARNING EXPERIENCES

*Our third realization was that each student has a different set of predominant learning modalities—that is, some combination of learning by listening, reading or viewing, touching, or doing* (Dunn and Dunn, 1993). The assumption that "if this teaching approach worked for me, it must be good for my students" may not fit all students; after all, we in academia are the minority who thrived in this educational system. We have "discovered" that teaching that accommodates a variety of learning modalities makes our instruction more effective and improves our students' learning. It was also crucial to become aware that not every student is a young version of us. Some will simply not possess the curiosity, interest, and attitudes that motivate scientists. Only a minority of our students will continue in scientific research. However, all of them will eventually be consumers of scientific knowledge, taxpayers who fund our research, and decision makers in voting booths and public offices. We therefore have a responsibility to improve our students' general scientific literacy and ocean literacy in particular. We need to help them develop the knowledge and skills required by citizens who will inevitably face scientific, environmental, and technological challenges.

## INQUIRY-BASED LEARNING AND TEACHING

In science teaching, *inquiry* refers to a way in which learners become engaged in scientific questions or problems—trying to solve them by making predictions and testing them, seeking evidence and information, formulating possible explanations, evaluating them in light of alternative explanations, and communicating their understanding (National Research Council, 2000). Inquiry "is far more flexible than the rigid sequence of steps commonly depicted in textbooks as the 'scientific method.' It is much more than just 'doing experiments,' and it is not confined to laboratories" (AAAS, 1993). There are several models of inquiry-based teaching and learning (e.g., Hassard, 2005). In our teaching, we use hands-on/minds-on laboratory activities and demonstrations, but other effective, inquiry-friendly approaches that we do not discuss here include the use of case studies, project-based assignments, and service learning.

We caution that just providing students with laboratory experiences does not necessarily imply that inquiry teaching and learning are occurring. For example, traditional laboratory exercises, in which students are asked to follow step-by-step, cookbook-style instructions, can illustrate a scientific principle or concept, teach students laboratory skills, and provide some hands-on experience—but they do not provide the "minds-on" aspect of inquiry. For the "hands-on/minds-on" approach to be successful in terms of fostering inquiry, students should be encouraged to ask questions, make predictions and test them, formulate possible explanations, and apply their knowledge in a variety of contexts.

Students do not enter our classes as blank slates ready to absorb new information. Rather, they arrive in class with a diverse set of conceptions (and sometimes misconceptions) based on their previous experiences. Inquiry-based approaches allow instructors to probe students' knowledge and identify misconceptions that may interfere with learning. Inquiry helps students understand science as a way of thinking and doing, encourages them to challenge their assumptions, and creates an environment in which they seek alternative solutions and explanations. Broadly applicable skills developed in the inquiry process—reasoning, problem-solving, and communication—will be useful to students throughout their lives.

One barrier to our application of an inquiry-based teaching approach was a concern that this instructional method would not allow us to cover all the curriculum material within the prescribed time. This worry is valid, considering our limited classroom time. We felt, however, that if the purpose of teaching is to promote meaningful learning experiences in which students not only gain foundational knowledge but also learn to apply and integrate concepts, as well as grow towards becoming self-directed learners, we had to consider an inquiry-based approach. Given students' feedback on how beneficial this approach was to their learning, we came to realize that less is often more. We advocate for inquiry-based teaching, but we do not believe that all subject matter should always be taught through inquiry or that all elements of inquiry (generating questions, gathering evidence, formulating explanations, applying knowledge to other situations, and communicating and justifying explanations [National Research Council, 2000]) must be present at all times. Effective teaching requires the use of a variety of strategies and approaches (e.g., Feller and Lotter, 2009) that should be adapted to the individual classroom, the individual learners, the size and dynamics of each class, and immediate and long-term learning objectives, among other factors.

## HOW TO USE THIS DOCUMENT

This document is comprised of five chapters, each focusing on one of the following physical concepts—density, pressure, buoyancy, heat and temperature, and gravity waves. For each, we provide background information followed by detailed descriptions and explanations of hands-on activities. The activities emphasize different aspects of each concept. This approach allows students to examine each concept from a variety of angles, apply what they have learned to new situations, and challenge their understanding. In addition, we point out several pedagogical approaches that can improve teaching and foster learning (see also Feller and Lotter, 2009).

The hands-on activities are presented here in the formats we use in our college-level classes, which are composed mostly of sophomore, junior, and senior science and education majors who have previously taken an introductory oceanography course. Graduate students and our colleagues also found some of these activities challenging. For other settings (e.g., students with different backgrounds) and other curricula, these activities can and should be adapted, with appropriate changes in the background material, class discussions, activity descriptions, and explanations. Science teachers who participated in our workshops have successfully adapted some of the activities to their middle- and high-school classes.

In our classes, activities are most often conducted at classroom stations through which teams of three to four members rotate. At times, we present them as a sequence of activities or demonstrations that the class follows collectively, with students seated in small groups to facilitate discussion. Working in small groups fosters collaborative thinking and learning. Often, we encourage a healthy competition among groups (e.g., with group quizzes) to add a level of excitement and challenge. During class, we use a Socratic teaching approach in the sense that students are presented with guiding questions. Students' questions during the activities are not always addressed by answers. Rather, we ask additional questions that lead them to examine their ideas and views. Students are asked to make predictions, conduct measurements, and find possible explanations for the phenomena they observe. Once students complete the activities, the class gathers for a summary discussion during which each group is asked to offer an explanation for a given activity. Providing students with time to verbally communicate their views and understanding is an essential part of our approach. It ensures that misconceptions or difficulties with concepts are identified, discussed, and ultimately resolved. The applications of a concept and its connections to ocean processes are highlighted during the discussion and through homework assignments.

A 90-minute class period is typically sufficient for students to complete four to six activities during the first hour, leaving approximately 30 minutes for group discussion. Note that each of these activities can stand alone or can be presented as a class demonstration. Most require simple and affordable equipment that is generally available in classrooms or homes. We purchased some equipment at specialized science education stores (e.g., https://www.arborsci.com/), and we constructed some equipment ourselves.

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## RELATED WEBSITES

- What is Inquiry-Based Science?
  *https://ssec.si.edu/stemvisions-blog/what-inquiry-based-science*
- Exploring Our Fluid Earth
  *https://manoa.hawaii.edu/exploringourfluidearth/*
- Science Education Resource Center (SERC), Pedagogy in Action, Teaching Methods
  *https://serc.carleton.edu/sp/library/pedagogies.html*

# CHAPTER 1. DENSITY

## PURPOSE OF ACTIVITIES

Density is a fundamental property of matter, and although it is taught in secondary school physical science, not all university-level students have a good grasp of the concept. Most students memorize the definition without giving much attention to its physical meaning, and many forget it shortly after the exam. In oceanography, density is used to characterize and follow water masses as a means to study ocean circulation. Many processes are caused by or reflect differences in the densities of adjacent water masses or differences in densities between fluids and solids. Plate tectonics and ocean basin formation, deep-water formation and thermohaline circulation, and carbon transport by particles sinking from surface waters to depth are a few examples of density-driven processes. The following set of activities is designed to review density, practice density calculations, and highlight links to oceanic processes.

## BACKGROUND

Density (noted as $\rho$) is a measure of the compactness of material—in other words, how much mass is "packed" into a given space. It is the mass per unit volume ($\rho = \frac{m}{V}$; units in kg/m$^3$ or g/cm$^3$), a property that is independent of the amount of material at hand. The density of water is about a thousand times greater than that of air. The density of water ranges from 998 kg/m$^3$ for freshwater at room temperature (e.g., see https://www.scribd.com/doc/238050947/Water-Density-Pipet-Calibration-Data) to nearly 1,250 kg/m$^3$ in salt lakes. The majority of ocean waters have a density range of 1,020–1,030 kg/m$^3$. The density of seawater is not measured directly; instead, it is calculated from measurements of water temperature, salinity, and pressure. Given the small range of density changes in the ocean, for convenience, seawater's density is expressed by the quantity *sigma-t* ($\sigma_t$), which is defined as $\sigma_t = \rho - 1000$.

Most of the variability in seawater density is due to changes in salinity and temperature. *A change in salinity reflects a change in the mass of dissolved salts* in a given volume of water. As salinity increases, due to evaporation or salt rejection during ice formation, the fluid's density increases, too. *A change in temperature results in a change in the volume of a parcel of water*. An increase in the temperature of a fluid results in an increase in the distance between molecules, causing the volume of the fluid parcel to increase and its density to decrease (its mass does not change). Cooling reduces the distance between molecules, causing the volume of the fluid parcel to decrease and its density to increase. The relationship between temperature and density is not linear, and the maximum density of pure water is reached near 4°C (see Denny, 2007; Garrison, 2007; or any other general oceanography textbook).

### Density, Stratification, and Mixing

*Stratification* refers to the arrangement of water masses in layers according to their densities. Water density increases with depth, but not at a constant rate. In open ocean regions (with the exception of polar seas), the water column is generally characterized by three distinct layers: an *upper mixed layer* (a layer of warm, less-dense water with temperature constant as a function of depth), the *thermocline* (a region in which the temperature decreases and density increases rapidly with increasing depth), and a *deep zone* of dense, colder water in which density increases slowly with depth. Salinity variations in open ocean regions generally have a smaller effect on density than do temperature variations. In other words, open-ocean seawater density is largely controlled by temperature. In contrast, in coastal regions affected by large riverine input and in polar regions where ice forms and melts, salinity plays an important role in determining water density and stratification.

Stratification forms an effective barrier for the exchange of nutrients and dissolved gases between the top, illuminated surface layer where phytoplankton can thrive, and the deep, nutrient-rich waters. Stratification therefore has important implications for biological and biogeochemical processes in the ocean. For example, periods of increased ocean stratification have been associated with decreases in surface phytoplankton biomass, most likely due to the suppression of upward nutrient transport (Behrenfeld et al., 2006; Doney, 2006). In coastal waters, where the flux of settling organic matter is high, prolonged periods of stratification can lead to hypoxia (low oxygen), causing mortality of fish, crabs, and other marine organisms.

Mixing of stratified layers requires work. As an analogy, think about how hard you need to shake a bottle of salad dressing to mix the oil and vinegar. Without energetic mixing (e.g., due to wind or breaking waves), the exchanges of gases and nutrients between surface and deep layers will occur by molecular diffusion and local stirring by organisms, which are slow, ineffective modes of transfer (Visser, 2007). The energy needed for mixing is, at a minimum, the difference in potential energy between the mixed and stratified fluids. (Some of the energy, most often the majority, is lost to heat.) Therefore, the more stratified the water column, the higher the energy needed for vertical mixing. (Advanced students can be asked to compute this energy requirement, using the concept that the fluid's center of gravity is higher in the mixed fluid relative to the stratified one [e.g., Denny, 1993]).

Density is fundamentally important to large-scale ocean circulation. An increase in the density of surface water, through a decrease in temperature (cooling) or an increase in salinity (ice formation and evaporation), results in gravitational instability (i.e., dense water overlying less-dense water) and sinking of surface waters to depth. Once a sinking water mass reaches a depth at which its density matches the ambient density, the mass flows horizontally, along "surfaces" of equal density. This process of dense-water formation and subsequent sinking is the driver of thermohaline circulation in the ocean. It is observed in low latitudes (e.g., the Gulf of Aqaba in the Red Sea, the Gulf of Lions in the Mediterranean Sea) as well as in high latitudes (e.g., deep water formation in the North Atlantic). Within the upper mixed layer, convective mixing occurs due to heat loss from surface waters (density driven) and due to wind and wave forcing (mechanically driven).

Density is also fundamentally important to lake processes. As winter approaches in high latitudes, for example, lake waters are cooled from the top. As the surface water's temperature decreases, its density increases, and when the upper waters become denser than the waters below, they sink. The warmer, less-dense water underneath the surface layer then upwells to replace the sinking water. If low air temperatures persist, these cooling and convective processes will eventually cool the entire lake to 4°C (the temperature of maximum density for freshwater at sea level). With yet further surface cooling, the density of the upper waters will decrease. The lake then becomes stably stratified, with denser water at the bottom and colder but less-dense water above. When surface waters further cool to 0°C, they begin to freeze. With continued cooling, the frozen layer deepens.

## DESCRIPTION OF ACTIVITIES

Activities 1.1–1.3 are used to review density, and Activities 1.4–1.6 highlight links to oceanic processes. Activities 1.1–1.3 emphasize the relationship between an object's mass, volume, and density and its sinking or floating behavior. These activities also allow students to practice measurement skills. Measurements and related concepts such as precision and accuracy, and statistical concepts such as average and standard deviation, can be introduced during class and/or provided as homework. In Activities 1.4–1.6, students examine relationships among density, stratification, and mixing, and then discuss applications to ocean processes.

Activities are set up at stations prior to class (typically four to five stations per 90-minute class period, with the choice of activities, level of difficulty, and depth of discussion dependent on the students' backgrounds). Students are asked to rotate among stations to complete the assignments. During this time, instructors move among the groups and guide students by asking probing questions. The last ~ 30 minutes of class are used for summary and discussion.

## ACTIVITY 1.1. WILL IT FLOAT? (Figure 1.1)

### Materials

- Two solid, approximately equal-volume wooden cubes, one made of balsa and the other of lignum vitae (from https://www.homesciencetools.com/product/density-cube-set/)
- Large, hollow metal ball (from https://www.wardsci.com/)
- Small Delrin ball or other solid plastic sphere (available at any hardware store)
- Container filled with room-temperature tap water
- Ruler or caliper
- Balance

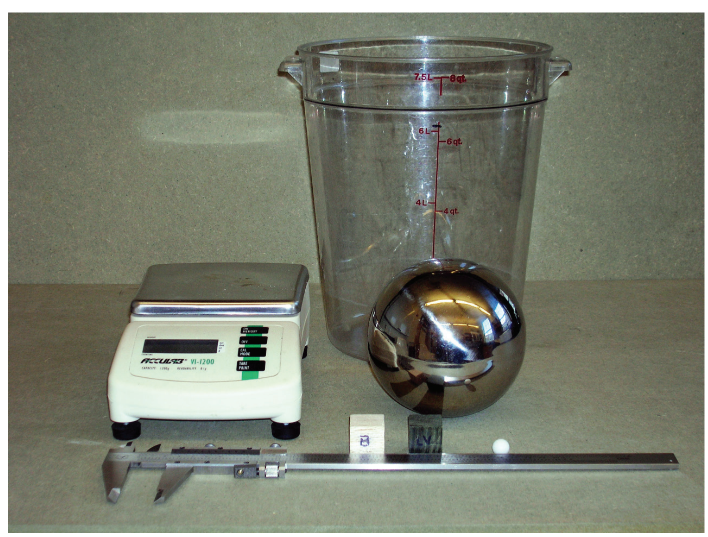

Figure 1.1. Materials for Activity 1.1.

### Instructions to the Students

1. Make a list of properties that you think determine whether an object sinks or floats.
2. Feel the objects provided and predict which will float in water and which will sink. What is the reasoning behind your prediction? Discuss your prediction with your group.
3. Test your prediction. Do your observations support your prediction? If not, how can you explain it?
4. Based on your observations, how would you revise your list of properties from Step 1?
5. Determine the mass and volume for each cube and ball. Can you suggest more than one method to obtain the volumes of the cubes and balls? (If time allows: How do the densities obtained by the different methods compare?)
6. What is the relationship, if any, between the masses of the objects and the sinking/floating behaviors you observed? What is the relationship, if any, between the volumes of the objects and the sinking/floating behaviors you observed?
7. Calculate the densities of the cubes, balls, and tap water. What is the relationship, if any, between the densities you calculated and the sinking/floating behaviors you observed?

### Explanation

In this activity, students experiment with four objects (found at https://www.fishersci.com/shop/products/density-cube-sets/S23980)—two types of solid wooden cubes, a hollow metal ball, and a solid plastic sphere. We use two types of wood that differ greatly in density: balsa, with a density range of 0.1–0.17 g/cm$^3$ (the specific cube we use has a mass of 2.25 g and a volume of 16.7 cm$^3$, hence a density of 0.13 g/cm$^3$), and lignum vitae, with a density range of 1.17–1.29 g/cm$^3$ (the specific cube we use has a mass of 19.6 g and a volume of 15.2 cm$^3$, hence a density of 1.29 g/cm$^3$). The densities of the small plastic ball and the larger hollow metal ball are 1.4 g/cm$^3$ (mass of 1.5 g and volume of 1.07 cm$^3$) and 0.14 g/cm$^3$ (mass of 144 g and volume of 1035 cm$^3$), respectively. Because the density of tap water at room temperature is ~ 1 g/cm$^3$, the balsa cube and the metal ball will float, and the lignum vitae cube and the plastic ball will sink.

This activity illustrates two key points: (1) The floating or sinking behavior of an object does not depend on its mass or volume alone but on the ratio between them—that is, its density. We discuss the commonly used phrase "heavy things sink, light things float" and point out the potential misconception that could arise. (2) The floating or sinking behavior of an object does not depend only on the material from which the object is made (e.g., addressing the common misconception that wood always floats). If time allows, a discussion on volume measurements (based on measured dimensions or volume displacement) can be brought in, leading to the concept of buoyancy, which is introduced in Chapter 3.

## ACTIVITY 1.2. CAN A CAN FLOAT? (Figure 1.2)

### Materials

- A can of Mountain Dew and a can of Diet Mountain Dew
- Large container filled with room-temperature tap water
- Caliper or ruler
- Balance
- 2-liter graduated cylinder

### Instructions to the Students

1. Examine the two cans. List similarities and differences between them.
2. What do you think the floating/sinking behavior of each can will be when placed in room-temperature tap water? Write the reasoning for your prediction.
3. Place the two cans in the tank. Be sure no bubbles cling to the cans. Does your observation agree with your prediction? How would you explain this observation?
4. How would you determine the density of each can? Try your approach. How do the densities of the cans compare to the density of tap water?
5. Are your density measurements in agreement with your observations? Why might there be a difference in density between the cans and/or between the cans and the water?

### Explanation

When students place the two cans in a tub of freshwater, the can of ordinary soda sinks and the can of diet soda floats (Figure 1.2). Calculated densities of the cans of Mountain Dew and Diet Mountain Dew that we use (including the can, liquid, and gas) are 1.024 g/cm$^3$ and 0.998 g/cm$^3$, respectively. The difference in density is due to differences in the mass of sweeteners added to the regular and diet cans. A can of ordinary Mountain Dew contains 46 g of sugar! It will leave a big impression on your students if you weigh out 46 g of sugar to demonstrate the amount of added sugar (see right hand side of Figure 1.2). Variations of this activity are available on the Internet. We caution that variability exists among different brands of soda and among cans within the same brand; in some cases, both diet and regular soda cans will float (or sink). Instructors should always test the cans before class. Alternatively, a case in which a can that is supposed to float does not can be turned into a


Figure 1.2. Difference in densities and, hence, sinking and floating behaviors between a can of ordinary soda (right) and a can of diet soda (left).

teachable moment where students are challenged to test their understanding. This activity is an example of a discrepant event (see discussion on p. 24). Because the cans look and feel similar, students do not expect them to be different in terms of their sinking and floating behaviors. During the activity, students often raise the question of how to measure the volume of the cans (by volume displacement or by measuring dimensions of the can and calculating the volume of a cylinder). We let them choose an approach and since each group uses the same cans, we compare density estimates obtained by each. If time allows, we ask each group to use both approaches and compare their density estimations. One could further develop this activity to include estimates of the precision of each approach, as well as discussions on measurement accuracy and error propagation.

## ACTIVITY 1.3. DENSITIES OF OCEANIC AND CONTINENTAL CRUSTS (Figure 1.3)

*This activity has been modified after one designed by Donald F. Collins, Warren-Wilson College.*

### Materials

- Rock samples of basalt (representative of oceanic crust) and granite (representative of continental crust)
- An overflow container with a spout and a 50-ml graduated cylinder to catch displaced water (alternatively, a large graduated cylinder or a container with gradation lines will work)
- Balance

### Instructions to the Students

1. Determine the densities of the two rock samples. How do the densities of granite and basalt compare?
2. The average elevation of land above sea level is 875 m. The average depth of the ocean floor is 3,794 m below sea level. Apply your density calculations and your previous knowledge about Earth's structure to explain this large difference in elevation between continents and ocean basins.
3. Textbook values of oceanic crust and continental crust are 2.9–3.0 g/cm$^3$ and 2.7–2.8 g/cm$^3$, respectively. How do these values compare to your measurements? If they differ, what may account for the differences between the values you obtained and those given in textbooks?
4. Given that Earth's mass is 5.9742 x 10$^{24}$ kg and that Earth's radius is 6,378 km, calculate the density of the planet. (*Challenge*: How would one determine Earth's mass?). How does Earth's density compare to the density of the rocks? What does this tell you about Earth's structure?

### Explanation

The densities of rock samples we use are 2.8 g/cm$^3$ for basalt (oceanic crust origin) and 2.6 g /cm$^3$ for granite (continental crust origin). Both types of crust overlie Earth's denser mantle (3.3–5.7 g/cm$^3$). Continental crust is thicker and less dense than the depth-averaged oceanic crust plus the overlying water and therefore floats higher on the mantle than does oceanic crust. During the activity and the subsequent class discussion, we highlight three issues. The first concerns volume measurements of irregular shapes by water displacement. This concept is later linked to a follow-up lesson on buoyancy (Chapter 3). Next, we discuss the issue of measurements and variability associated with measurements. Science students are accustomed to seeing textbook values of quantities that represent averages, often without


Figure 1.3. Materials for Activity 1.3.

## BOX 1.1. OBTAINING THE MASS AND DENSITY OF PLANET EARTH

Earth's mass can be computed from Newton's laws:

1. Newton's Law of Universal Gravitation states that the force (attractive force) that two bodies exert on each other is directly proportional to the product of their masses ($m_1$, $m_2$) and inversely proportional to the square of the distance between them ($L$): $F = Gm_1m_2/L^2$, where $G$ is the gravitational constant ($G = 6.7 \times 10^{-11}$ N m$^2$/kg$^2$). If we assume that the body is near Earth's surface, then the planet's radius can be used as the distance between the body and Earth.
2. Newton's Second Law states that the force attracting a body to Earth equals its mass ($m$) times the gravitational acceleration ($g$): $F = mg$, where, for Earth's surface, $g = 980$ cm/s$^2$ ($g$ itself can be computed, for example, from the period of a pendulum).

Let $m_1$ be Earth's mass and $m_2$ be a body's mass:
$F = m_2g = Gm_1m_2/L^2$. Earth's mass is therefore $m_1 = gL^2/G \approx 6 \times 10^{24}$ kg. Dividing by Earth's volume ($4/3\pi r^3$, where $r$ is Earth's radius; here we used an average of 6,373 km), we obtain Earth's density (5,515 kg/m$^3$ or 5.515 g/cm$^3$).

any statistical information on the associated uncertainties or natural variance. Furthermore, some students believe that if you don't get the exact value provided in a textbook, you are wrong. At the end of the class, we compare the groups' density measurements and their methods, and then discuss potential sources of variability in measurements and what it is that textbook values actually represent. (Statistical concepts of averages and standard deviations can also be brought in here.) Last, we highlight applications—how differences in the densities and thicknesses of continental and oceanic crusts shape Earth's topography, as well as their relation to plate tectonic processes. For a derivation of Earth's average mass and density, see Box 1.1.

## ACTIVITY 1.4. EFFECTS OF TEMPERATURE AND SALINITY ON DENSITY AND STRATIFICATION (Figure 1.4)

### Materials

- Rectangular tank with a divider (from https://www.wardsci.com/store/product/10548736/weather-water-tanks-fronts-and-thermoclines-lab-activity)
- Bottle containing pre-made salt solution (approximately 75 g salt dissolved in 1 L water: kosher salt yields a clear solution while a solution made with table salt, at high concentrations, appears milky)
- Food coloring (two different colors)
- Ice
- Beakers

### Instructions to the Students

1. Fill a beaker with tap water.
2. Place water from the beaker in one compartment of the tank and water from the salt-solution bottle in the other. Add a few drops of one food coloring to one compartment and a few drops of the other food coloring to the other compartment. What do you predict will happen when you remove the divider between the compartments? Explain your reasoning.
3. Measure the densities of the room-temperature tap water and the salt solution.
4. Test your prediction by removing the tank divider. What happens? Are your observations consistent with the densities you measured?

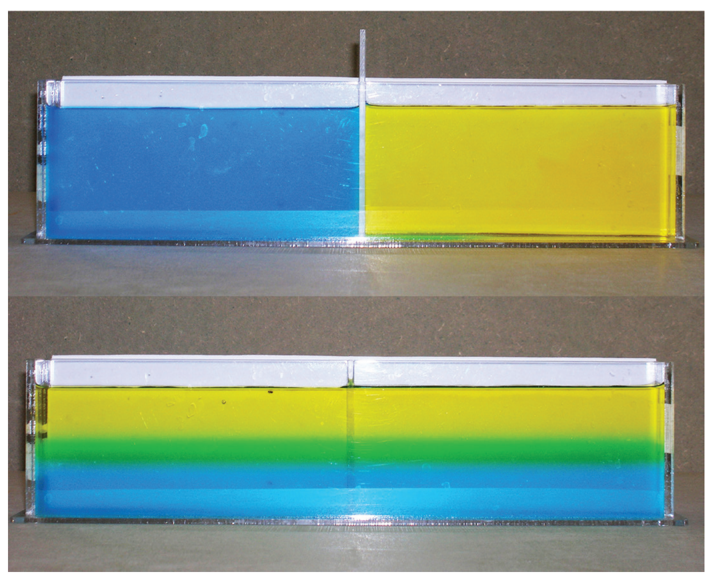

Figure 1.4. Tank before (top) and after removal of divider (bottom).

5. Empty the tank and fill one beaker with hot tap water and one beaker with ice-cold water. Add a few drops of food coloring to each of the beakers (different color to each beaker).
6. Place the hot water in one tank compartment and the ice-cold water in the other. Repeat Steps 3–5. After removing the divider and observing the new equilibrium in the tank, place your fingertips on top of the fluid surface and slowly move your hand down toward the bottom of the tank. Can you feel the temperature change?
7. How might the effects of climate change, such as warming and melting of sea ice, affect the vertical structure of the water column? Discuss possible scenarios with your group (alternatively, this question can be given as a homework assignment).

### Explanation

This activity demonstrates that fluids arrange into layers according to their densities. The two "water masses" (Figure 1.4)—salt (blue) vs. fresh (yellow), or cold (blue) vs. warm (yellow)—are initially separated by the tank's divider. When the divider is removed, the denser water (salt water or cold water [blue]) sinks to the bottom of the container and the less-dense water (fresh or warm water [yellow]) floats above, forming a stratified column. In the process, an internal wave is formed in the tank (which we discuss in more detail in Chapter 5, Gravity Waves).

## ACTIVITY 1.5. EFFECT OF STRATIFICATION ON MIXING (Figure 1.5)

*This activity is based on a demonstration communicated to us by Peter Franks, University of California, San Diego. See Franks and Franks (2009) for details of that physical simulation.*

### Materials

- Tank containing tap water
- Tank containing stratified fluid*
- Hair dryer
- Food coloring (two different colors)
- Long pipettes

*To prepare a tank with a two-layer stratified fluid, fill half to three-quarters of the tank with a strong saltwater solution (see Activity 1.4). Place a piece of thin foam (same width as the tank) over the water, and carefully pour warm tap water over the foam. Then remove the foam piece carefully, without stirring and mixing the fluids. For another technique, see Franks and Franks (2009).

### Instructions to the Students

1. Predict in which tank a dye introduced at the surface will mix more easily throughout the tank.
2. In the tank with the nonstratified water column, use a long pipette to carefully inject a few drops of food coloring at the water's surface. Using the hair dryer, generate a "wind" flowing roughly parallel to the fluid's surface, and observe how the dye mixes.
3. With the tank containing the two-layer fluid, use the long pipette to carefully inject a few drops of food coloring at the water's surface and a few drops of a different food coloring at the bottom of the tank. Using the hair dryer, generate a wind similar to the one you generated in Step 2. Compare your observations to what you saw happen in the nonstratified tank.
4. In light of your observations, predict and discuss with your group some potential effects of global warming on stratification and mixing in the ocean and in lakes. What might be some consequences for marine organisms?

### Explanation

In the nonstratified water column (Figure 1.5, left panel), red dye added at the fluid's surface initially sinks because its density is slightly higher than that of the water (Figure 1.5, top left). After a short time of exposure to a stress on the surface ("wind" generated by a hair dryer), the dye mixes throughout the water column (Figure 1.5, bottom left). In the stratified tank (right panel), the pycnocline, the region of sharp density change between the layers, forms an effective barrier to mixing (Figure 1.5, top right). More energy is required to mix the two layers, and the "wind" generated by the hair dryer is no longer sufficient to mix the entire water column. As a result, the red dye mixes only within

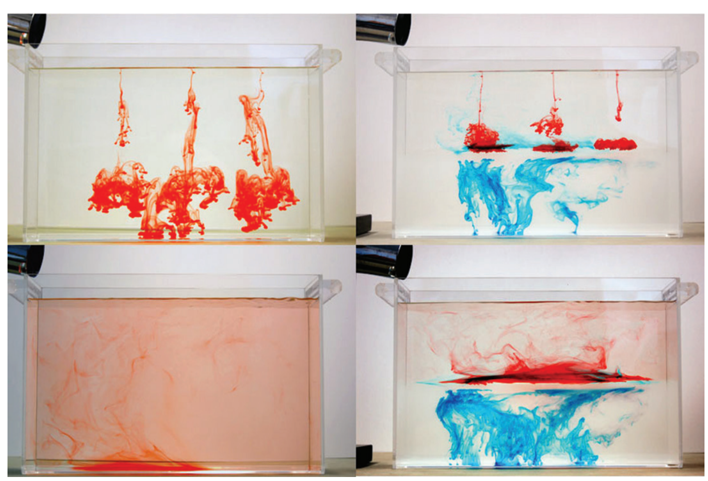

Figure 1.5. Tanks with dye before (top) and after (bottom) application of mechanical forcing (blowing of a air dryer parallel to top). Left side: nonstratified tank, right side: density-stratified tank.

the upper layer, analogous to the upper mixed layer in oceans and lakes (Figure 1.5, bottom right). Calculations of the energy required to increase the depth of the pycnocline by mixing, raising the center of gravity of the fluid, can be used in conjunction with this activity (e.g., Denny, 2007).

## ACTIVITY 1.6. CONVECTION UNDER ICE (Figure 1.6)

### Materials

- At least four blocks of colored ice (add food coloring to water, then freeze in food-storage containers)
- Two large transparent containers—one filled with tap water and one filled with saltwater (both at room temperature)*

*It is necessary to replace water in the containers each time a new group of students arrives at the station. As ice melts, the color mixes with water and after a while it becomes difficult to observe the pattern of flow.

### Instructions to the Students

1. Place a block of colored ice in the container filled with tap water. As the ice melts, observe and explain the behavior of the fluids.
2. Place the other block of colored ice in the container filled with saltwater. As the ice melts, observe and explain the behavior of the fluids. Compare these observations with what you saw in Step 1.

*Note to instructor*: Advanced students can be asked to observe whether the fluids' behavior in the tanks depends on whether the ice is near the tank walls or at the center of the tank and relate these observations to likely oceanic scenarios (e.g., convection chimneys in the open ocean vs. convection on a shelf).

### Explanation

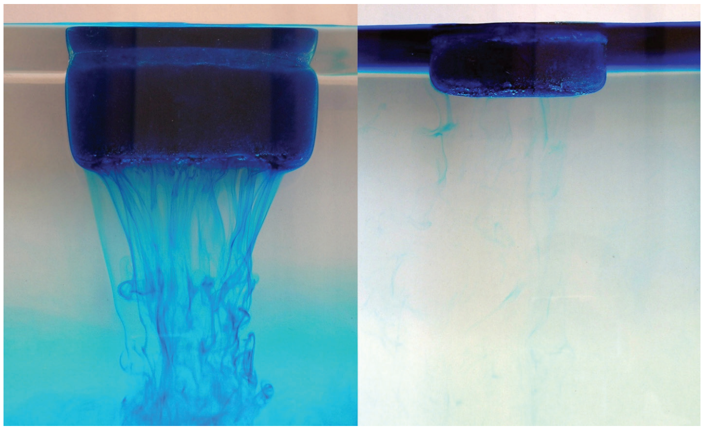

Figure 1.6. Convection associated with melting of a colored ice block in tap water (left) and saltwater (right).

Figure 1.6, left panel: In tap water, the ice block floats because the density of ice is lower than that of freshwater. As the ice melts, however, cold, colored meltwater sinks to the bottom because it is denser than the tap water. Warmer water from the bottom is then displaced and upwells, resulting in a convective flow visible in the dye patterns. Ice melting in the center of the tank is analogous to a convection "chimney" formed in the open ocean, while ice melting at the tank's edge is analogous to a chimney on a continental shelf (near a land mass). Such chimneys in the ocean, created and sustained by convective processes, appear as "columns" of mixed water that flow downwards. For a given set of oceanic and meteorological conditions, open-water convection tends to entrain (mix with) more of the surrounding waters than does convection near a land mass. The open-ocean case therefore results in downwelled water that is less dense.

Figure 1.6, right panel: The ice block is floating in dense, salty water. As the ice melts, only a small amount of dye sinks because the density of the saltwater is greater than the density of the newly melted, fresh, ice-cold water. Most of the meltwater accumulates in a surface layer on top of the denser salt layer.

## SUPPLEMENTARY ACTIVITY (Figure 1.7)

Time permitting, students' understanding of the concept of density can be assessed at the end of the lesson by giving them a Galileo thermometer (Figure 1.7; inexpensive and available online), a container with hot water, and a container with cold water, and asking them to explain how the thermometer works. A Galileo thermometer is made of a sealed glass tube containing a clear fluid and calibrated, fluid-containing glass balls with metal tags attached to them. The balls, each having a slightly different density, are all suspended in the clear fluid. They are sealed and therefore each has a constant volume and mass, hence, constant density. What changes as a result of heating or cooling is the density of the surrounding fluid. The change in relative density between the glass balls and the clear fluid causes the balls to rise or sink and rearrange according to their equilibrium densities. Usually the balls separate into two groups, one near the bottom and one near the top of the column. Temperature is then read from metal disks attached to the balls: the reading on the disk of the lowermost ball of the group near the top of the column indicates the temperature. We caution that it takes a long time for a Galileo thermometer to register changes in temperature after being switched from a warm water bath to a cold water bath (or vice versa), due to the slow rate at which the internal liquid changes temperature. This slow

Figure 1.7. A Galileo thermometer.

equilibration is especially pronounced when the thermometer is placed in an ice bath, because the cold (dense) liquid remains near the bottom. Periodically tilting the thermometer can reduce the wait time. For a short-term demonstration, it is better to compare two thermometers, one placed in a warm water bath and one placed in a cold water bath.

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# ENCOURAGING STUDENTS TO ASK QUESTIONS: A WALK THROUGH A RICH ENVIRONMENT

BASED ON WELLER, 1988

Questioning is an integral part of science inquiry (National Research Council, 2000) and holds many educational merits. The National Research Council (2000, p. 29) describes a learner's engaging in "scientifically oriented questions" as one of the five essential features of classroom inquiry. Students' questions may reveal much about their understanding and reasoning, and uncover alternative frameworks and misconceptions. Students' asking of questions can stimulate their curiosity and motivation, help them develop critical and independent thinking skills, and make them active participants. However, in a typical lecture, students seldom ask questions; questioning is done primarily by the instructor. When senior undergraduates in our program were asked why they rarely asked questions in class, the two most common answers were: (1) a fear of appearing stupid, and (2) a class atmosphere not conducive to asking questions. Many students commented that their formal educational experiences had led them to develop the notion that their expected role as learners was to be present in class, take notes, and complete homework assignments and exams. The skill of asking questions was not one that had been emphasized as part of their formal education.

We describe here an approach we use to encourage students to ask questions.

In the first class period of a course, we take the students on a walk through a rich, stimulating environment. The purpose of the walk is to expose them to an object-rich environment that will incite spontaneous questions. This approach is derived from a parallel elementary-school approach intended to elicit questions from young students (Jelly, 2001).

For the rich environment, we use the University of Maine aquaculture facility, where tropical fish are raised for research and commercial purposes. We do not tell students anything about the environment prior to the walk. We instruct them only to write down questions that come to mind as they explore the environment, focusing on questions that truly interest them (rather than questions one might find in a textbook). After about 30 minutes of unconstrained exploration, each student is asked to choose three to five favorite questions from his/her list to contribute to a class list. The class list can be compiled electronically or manually using white boards or flip charts, allowing students to visually appreciate the quantity, quality, and diversity of the questions they generated. Examples of students' questions during the aquaculture walk include: "Do fish play?" "Do algae promote or inhibit spawning?" "How do you transport the tropical fish in extreme weather conditions, and what is their mortality rate in the process?"

Next, we ask students to form teams, and each team is asked to categorize the questions based on similar characteristics. A representative from each team explains to the class the reasoning for the choice of categories. These cooperative learning techniques of classroom organization encourage all the students to carefully consider all the questions, and eliminate the "blurting out" of categories by a small number of students. For example, in 2007, the categories developed by the three small groups were: Group A—biology, facility, environment, business; Group B—environment, life cycle of fish, facility/marketing; and Group C—exploratory, biology/ecosystem, technical, facility/economics. This activity may be the first time that some of the students have categorized raw data without any instructor hints.

For closure, we ask the students to share their views on how their walk, questioning, and categorization might resemble what scientists do in the initial exploratory phase of a research undertaking. We also ask students to describe what they believe makes a question a good science question. We discuss this topic as a class, referring to questions they generated, to illustrate characteristics of good science questions. The students often respond that a good science question should be as specific as possible and not involve nonscience aspects of belief, politics, and ethics. Additional aspects that we bring up during the discussion include: A good science question should (1) be as specific as possible, isolating the essentials of a problem; (2) not "assume an answer" (Sagan, 1996), but create falsifiable, alternative hypotheses as to what are answers to the question; (3) not involve pseudoscience (Derry, 1999; Sagan, 1996); and (4) not involve something we cannot acquire information about (Sagan, 1996). For deeper discussions of these aspects of scientific questioning, we recommend Derry (1999), Sagan (1996, Chapter 12, pages 201–218), and Atkins (2003, pages 3–4). Finally, we discuss the power of questioning in learning and ask students to share their feelings about asking questions in class. We use this opportunity to remind students that questioning will be an integral part of the class.

This exercise sets the tone for our course, increases students' comfort with asking questions, and ultimately enhances student learning. As extensions of this approach, students could be asked to seek answers for their own questions as a homework or term-paper assignment. The exercise could also be used in the middle of a course to capture students' interest when a new topic is introduced. Note that a rich environment does not have to be a specialized facility. Class demonstrations, video clips, computer simulations, and/or photos and images could readily serve to stimulate students' questioning.

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# CHAPTER 2. PRESSURE

## PURPOSE OF ACTIVITIES

This set of activities is intended to help students understand the concept of pressure in fluids. Teaching about pressure through its mathematical expressions (i.e., the hydrostatic equation, Bernoulli's equation) may not reach less mathematically oriented students. Thus, we use a series of activities that allows students to examine pressure from different angles. We begin by revisiting the physical definition of pressure and introducing examples from everyday life. This structure provides students with a familiar entry point into an often poorly understood concept and helps motivate students by making learning more relevant. Then, through hands-on, inquiry-based activities, we illustrate the concepts of hydrostatic pressure, compressibility of gases under pressure (i.e., Boyle's Law), and pressure in moving fluids (i.e., Bernoulli's Principle). We highlight the significance of these principles to processes in the ocean, from ocean circulation to the evolution of adaptations commonly found in marine organisms today.

## BACKGROUND

Pressure ($P$) is defined as the force ($F$) applied on a unit area ($A$) in a direction perpendicular to that area:

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

Thus, pressure depends on the area over which a given force is distributed. Pressure is a scalar, and hence has no directionality. A directional force from high to low pressure is applied on an object when the pressure varies across an object. The commonly used unit of pressure is Pascal (Pa), where 1 Pa = 1 N/m$^2$ = kg/m·s$^2$ (N = Newton). Units such as pounds per square inch (psi), bar, and standard atmosphere (atm) are also used in oceanic and atmospheric applications.

Many phenomena encountered daily are associated with the concept of pressure. Among them are wind, differences in the performances of a sharp vs. a blunt chopping knife or axe, and drinking with a straw. Atmospheric pressure at sea level has a magnitude of nearly $10^5$ Pa. Our bodies do not collapse as a result of this pressure because no net force is applied on them (an equal pressure exists within the body). Our senses do not detect absolute pressure, but do detect change in pressure (e.g., a change in pressure that is generated within gas-filled cavities when we dive or fly).

Although students may not realize it, pressure varies from place to place, both in the ocean and in the atmosphere. Spatial variations in pressure are the driving force for ocean currents and winds. For example, the trade winds blow from the normally stable high-pressure area over the eastern Pacific to the low-pressure area over the western Pacific. However, for reasons that are not yet fully understood, these pressure patterns shift every three to eight years, causing the trade winds to weaken and then reverse direction. This change in atmospheric pressure is called the Southern Oscillation. Equatorial Pacific changes in ocean circulation associated with the Southern Oscillation result in the phenomenon known as El Niño, which has serious global consequences.

Pressure in the ocean increases nearly linearly with depth. Different marine organisms are adapted to life at a particular depth range. Gas-filled cavities within animals and other organisms are compressed under pressure (see below). Additionally, the solubility of gases is affected by pressure, with important consequences for the diving physiology of both humans and marine organisms. Pressure not only puts constraints on marine organisms, but they can also use it. For example, pressure changes associated with the flow of water over mounds and other protrusions enhance the flow's velocity, and thus the delivery of food to suspension feeders (e.g., barnacles), and oxygenated water into the burrows of sediment-dwelling organisms (see below).

### Hydrostatic Pressure (Fluids at Rest)

The pressure at a given depth in the ocean is a result of the force (weight) exerted by both the water column and air column above it. This pressure, in fluids at rest, is termed "static pressure" or "hydrostatic pressure." Hydrostatic pressure ($P_h$) is a function of the density of a fluid and the height of the fluid column (depth). The relationship is defined by the hydrostatic equation $P = \rho g z$, where $\rho$ is the depth-averaged density, $g$ the gravitational acceleration, and z the height of the water column (see Box 2.1 for the derivation). The hydrostatic equation is central to studies of ocean circulation. For example, geostrophic currents (such as ocean gyres and Gulf Stream rings) are determined by the balance between horizontal pressure gradients and the Coriolis acceleration (an acceleration resulting from Earth's rotation). Differences in hydrostatic pressure between two locations result in a force per unit volume exerted on the fluid (air or water)

## BOX 2.1. CALCULATING HYDROSTATIC PRESSURE

Assume a water column with a cross-sectional area, $A$, and a depth (height), $z$. The volume of the water column is $Az$. The force that this column exerts on a given cross section is $F$ = weight = $mg$, where $m$ is the mass of water above the cross section and $g$ is gravitational acceleration. The mass can be conveniently expressed in terms of the density (here assumed constant) and the volume of the water: $m = \rho V$. Thus, $F = \rho Vg$. The force per unit area (the pressure, $P$) is, therefore, $P = \rho Vg/A = \rho(Az)g/A = \rho gz$. If density varies with depth (a change usually smaller than 1% in the ocean), the depth-averaged density is used instead of density (calculated by integrating density with respect to depth and dividing by the water column's depth). When measuring pressure in fluids, the hydrostatic equation comes in very handy. Devices such as manometers (Activity 2.4) are used to measure pressure relative to a reference pressure (usually atmospheric pressure).

acting from the region of high pressure to the region of low pressure. Because of Earth's rotation, the resulting fluid motion is not "downhill" from high to low pressure (as the fluid would do in a nonrotating environment), but rather along lines of constant pressure. At the equator, however, where the Coriolis effect is small, winds and currents are mostly down pressure gradients.

It is impractical to reliably measure horizontal changes in pressure along surfaces of fixed depths in the ocean because pressure and depth are scaled versions of the same vertical coordinate (to a first order). Instead, oceanographers use the dynamic height method in which two equal pressure reference points are chosen and the depth-integrated densities of the water columns above these reference points are calculated and compared. It is assumed that these two reference points are located on an isobaric "surface" (an imaginary surface where pressure is the same everywhere), and therefore there is no horizontal water motion at that chosen depth. If $\rho_1 \neq \rho_2$ (where $\rho_1$ and $\rho_2$ are the depth-integrated densities at reference points 1 and 2, respectively), then $z_1$ and $z_2$ (the heights of the water column above reference points 1 and 2) must be different. Differences in the heights of the water column above the reference depth are used to calculate sea surface slopes; for example, across the Gulf Stream (about 70-km wide), the surface height drops more than 1 m. The calculated slope is proportional to the pressure gradient that is required for estimations of geostrophic currents' speeds (e.g., Figure 10.7 at https://open.umn.edu/opentextbooks/textbooks/20). Today, it is possible to determine sea-surface slopes using satellite altimetry.

Two other important points should be mentioned with respect to hydrostatic pressure. The first is the transmission of pressure through the fluid. Pressure that is applied to one part of a fluid is transmitted throughout the entire fluid (known as Pascal's Principle). Information about the occurrence of a pressure change within the fluid propagates by sound waves at the speed of sound (~ 1,500 m/s), which in our laboratory setups (e.g., a Cartesian diver in Chapter 3) seems instantaneous. If you take a balloon full of water and submerge it under water, the hydrostatic pressure outside the balloon equals the pressure inside it and the balloon maintains its shape and size. This principle is the reason why you don't feel pressure on your body (except for air cavities; see below) when you dive. Transmission of pressure by fluids is the principle used in hydraulic devices (e.g., car lifts in service stations, hydraulic jacks, construction machines that are used for lifting heavy loads).

### Compressibility of Gases Under Pressure

In the ocean, pressure increases at a rate of 1 atm ($10^5$ Pa) per 10 m. Organisms that live or dive to great depths are therefore subjected to high compression forces due to the weight of the water column above them. One of the primary differences between water and gases is that water is a highly incompressible fluid and gases are compressible. The volume of a fixed amount of gas is inversely proportional to the pressure within it (known as Boyle's Law); if the pressure doubles, the volume of the gas shrinks by half. Because the human body is comprised mostly of water, it does not compress significantly when diving in water. Pressure is only felt in sealed air cavities such as sinuses, ears, and lungs. This is why a person's ears may hurt when diving only a few meters deep in a pool. Marine mammals that dive to great depths have developed adaptations to overcome potential damage to air cavities such as lungs. Conversely, Boyle's Law also illustrates the danger of expanding gases when pressure is reduced by moving to shallower depths. When a scuba diver breathes compressed air at a depth of 10 m (where the total pressure is 2 atm) and then ascends to the surface while holding his/her breath, the air in the lungs will try to expand to twice the volume. Some air must be released or the lungs may rupture. Similar damage would occur to the gas bladders of many species of fish if they ascended too rapidly. Therefore, some species of bottom-dwelling fish are restricted in their vertical movement, and may be killed when hauled up by fishing gear. Other species have evolved pathways to rapidly vent their gas bladders and are therefore not restricted in their vertical movements.

In the discussion above, we assumed temperature to be constant. It may be useful to ask students how changes in temperature might affect changes in volume of a submerged object. The Ideal Gas Law states that for a given volume of gas, pressure increases with temperature (discussion of molecular kinetic energy will fit well here). However, in the ocean, the change of temperature with depth has a much smaller range (about 10% in Kelvin units through the full ocean depth) than the change of pressure with depth (1 atm every 10 m). Thus, volume changes of gas-filled cavities as a function of depth are dominated by pressure.

### Accelerating Fluids: Bernoulli's Principle

When the velocity of a fluid changes along its path, simultaneous changes in pressure are at play. The relationship between fluid pressure and its velocity, known as Bernoulli's Principle (Box 2.2), can be derived from the principle of conservation of energy or from Newton's Second Law ($F = ma$). Many organisms, such as sponges, ascidians, and other suspension feeders, appear to take advantage of the flow of surrounding water to supplement their pumping activity (Vogel, 1978). For example, the burrowing shrimp *Callianassa filholi* builds large mounds surrounding an opening to the outside. Similar to a house chimney, the flow passing over the mound has to accelerate (accommodating a smaller cross section); coincident with this acceleration is a lower pressure above the opening, creating an updraft within the ventilation tube.

## DESCRIPTION OF ACTIVITIES

We often begin the discussion of pressure by showing an image of a ballerina standing on one foot and an elephant standing on four feet, and asking students to predict which exerts a larger pressure on the floor. Students are asked to cast their votes and then calculate the pressures (assuming the mass of an elephant is 6000 kg, the mass of the ballerina is 45 kg, the radius of one foot of the elephant is 30 cm, and the radius of the tip of the ballet shoe is 1 cm). (Recall that the force [$F$] is equal to the weight [not to be confused with mass] of the object: $F$ = weight = $mg$, where $m$ is the mass and $g$ is the gravitational acceleration 9.8 m/s$^2$).

We use Activities 2.1 and 2.2 as powerful illustrations of the concept of pressure. Hydrostatic pressure is demonstrated in

## BOX 2.2. BERNOULLI'S PRINCIPLE

Assume you have an incompressible fluid moving in a steady, continuous stream, where viscosity forces are assumed to be negligible (no friction losses). Several forms of energy are at play: (1) gravitational potential energy associated with the mass of the fluid, $E_p = mgz$, (2) compressional potential energy of the fluid, $PV$, and (3) mechanical kinetic energy that is proportional to the velocity of the fluid, $E_k = mv^2/2$. The total energy is the sum of all forms. From the principle of conservation of energy, if no work is done on the fluid, the total energy at two points along the path of the flow is the same:

$$m_1 \frac{v_1^2}{2} + m_1 gz + P_1 V_1 = m_2 \frac{v_2^2}{2} + m_2 gz + P_2 V_2 .$$

If z and density are the same along the flow (same fluid flowing in a horizontal pipe), we can cancel the gravitational potential energy terms. Doing just that and dividing by the volume yields:

$$\rho_1 \frac{v_1^2}{2} + P_1 = \rho_2 \frac{v_2^2}{2} + P_2 .$$

Thus, changes in velocity along the flow (an acceleration) are associated with changes in pressure.

Bernoulli's Principle holds significant implications for the calculations of aerodynamic lift, is used to measure velocity of airplanes (the Pitot tube seen on the side of the cockpit of small jets), and makes it possible for wind-powered vehicles to travel faster than the wind that propels them.

Activities 2.3 and 2.4. Although these two activities highlight the same principle, students often comment that doing both activities greatly improved their understanding of hydrostatic pressure. They were "forced" to transfer knowledge from one situation to another and the processes prompted them to re-evaluate their understanding. The use of multiple activities to illustrate the same principle also provides the instructor with additional opportunities for assessment. Activities 2.5 and 2.6 are designed to demonstrate the concept of compressibility of gases under pressure, where Activity 2.5 provides a qualitative illustration, and Activity 2.6 is a quantitative presentation of Boyle's Law. To demonstrate Bernoulli's Principle, we use Activity 2.7. Activities are set up at stations, as described in Chapter 1, and can, alternatively, be used as class demonstrations.

## ACTIVITY 2.1. BED OF NAILS (Figure 2.1)

### Materials

- Two square wooden boards (same size); one board has a single nail in the center; the other board has a grid of nails (15 by 15 nails)
- Ring stand
- Balloons of the same material, size, and shape
- A ring to serve as a weight

We insert a small clear piece of tubing onto the ring stand pole to make it easy to move the ring along the stand pole and be placed on the balloon. However, any kind of weight that can be placed on the balloon will work.

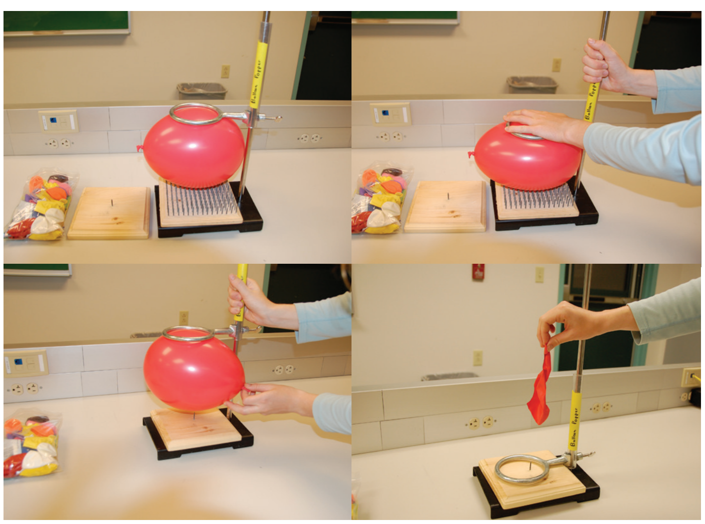

Figure 2.1. Activity 2.1 setup and experiment with bed of nails (top) and a single nail (bottom).

### Instructions to the Students

1. Predict what will happen to a balloon when you place it on each of the boards and apply approximately the same force. Explain your reasoning.
2. Test your prediction.

### Explanation

When a balloon is placed on a bed of nails (Figure 2.1, top left panel), the force that is applied is distributed over a large area (the sum of the heads of all the nails in contact with the balloon). The resultant pressure is not sufficient to cause the balloon to pop (Figure 2.1, top right panel). When the balloon is placed on a single nail, it takes only a weak force for the balloon to pop because the force is now distributed over a smaller area (the area in contact with one nail; Figure 2.1, bottom left panel), and the higher pressure causes the balloon to pop (Figure 2.1, bottom right panel). For that same reason, lying on a bed of nails may feel prickly but will not hurt you, while stepping on one nail may poke a hole in your foot. The same argument can be used to explain why sharpening a chopping knife or an axe makes them more effective for cutting.

## 2.2. PERCEPTION OF WEIGHT (Figure 2.2)

### Materials

- Large, hollow steel ball (diameter 12.5 cm and a mass of 144 g; from https://www.wardsci.com/store/product/8888910/steel-sphere-density-set)
- Small, solid steel ball (diameter 3.2 cm and a mass of 129 g; from https://www.wardsci.com/store/)
- Two large identical funnels
- A balance for weighing each ball

Figure 2.2. Materials for Activity 2.2 (left) and experiment (right).

## Instructions to the Students

1. Simultaneously, hold the two balls in the palms of your hands. Which one feels heavier?
2. Choose a volunteer and ask this person to close his/her eyes. Place each ball in a funnel and ask the volunteer to hold each funnel by the bottom of the collar. Ask the volunteer to indicate which ball is heavier and record his/her answer. Repeat this experiment with another volunteer(s).
3. Was the perception of weight when holding the funnels different from the "free-hand" test? Why?
4. Weigh the balls to determine which one is heavier. Explain your observations.

## Explanation

When holding each ball in the palm of a hand, the large ball feels lighter than the small ball. The force ($F = mg$) exerted by the large ball is actually larger, compared to the small ball. However, because the force is distributed over a larger area, the pressure ($P = F/A$) is smaller, and it feels lighter. When the balls are placed in the funnels and held by the collars, the surface area to which the force is applied is similar for both balls and you will notice that the larger ball is slightly heavier, which is confirmed using a balance.

# 2.3. READY, SET, SQUIRT (Figure 2.3)

## Materials

- A pipe with one small exit hole drilled near the bottom and seven large holes drilled along it and plugged with rubber stoppers (Figure 2.3, top). The separation between the hole centers is 5 cm (can be varied). A simpler version of this activity can be done using the mid sections of 2-liter soda bottles taped together (Sharon Franks, UCSD, *pers. comm.*, June 2009)
- A pipe with three different-size holes drilled at the same height (Figure 2.3, middle)
- Large tub
- Ruler
- Jug with water
- Paper towels

## Instructions to the Students

Prior to the activity, we review the hydrostatic equations and provide the students with the following instructions (some may find that discussing the hydrostatic equation works best AFTER doing part A).

### *Part A*

1. You have a pipe with one small exit hole near the bottom and several large holes plugged with rubber stoppers. You can fix the height of the water column above the exit hole by simultaneously covering the bottom exit hole with your finger and filling the tube until water flows out one of the upper large holes (after removing a stopper from the hole). Make sure you have placed the ruler perpendicular to the bottom of the pipe.

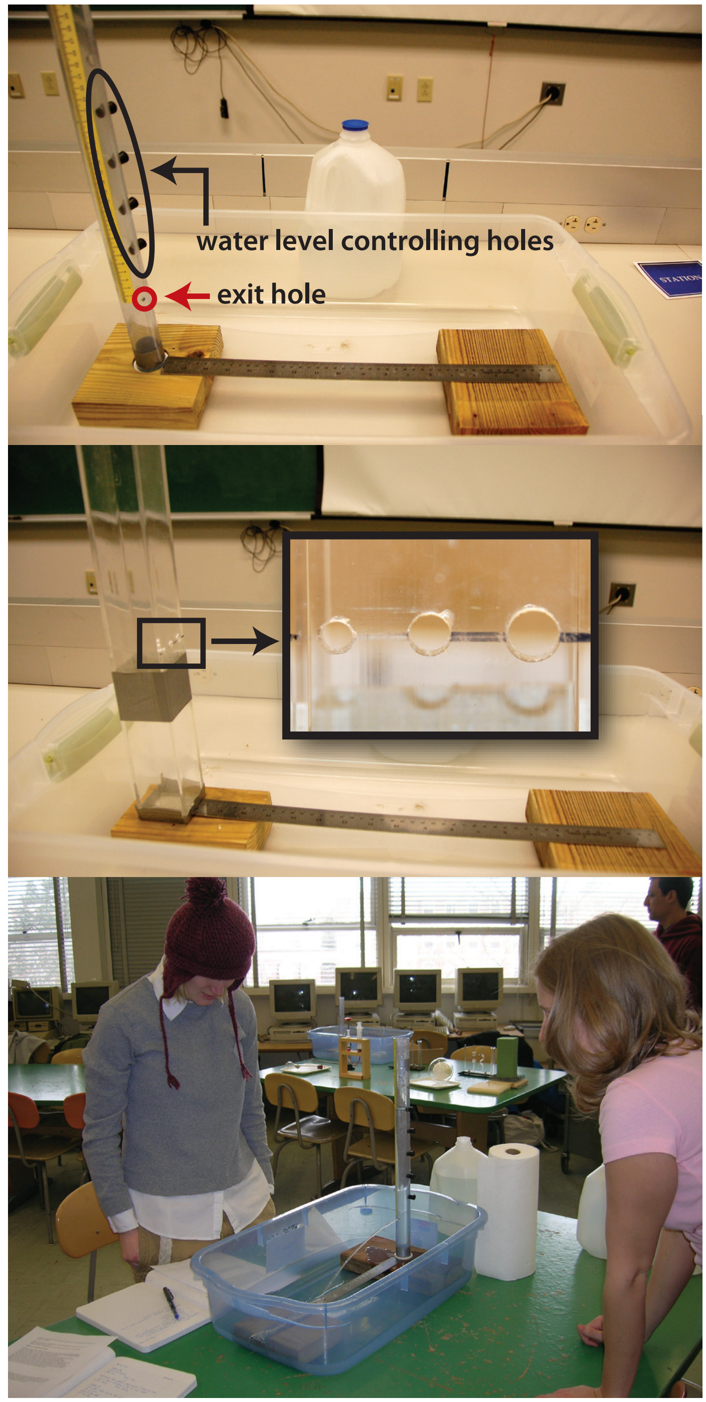


Figure 2.3. Materials for Activity 2.3, Part A (top) and Part B (middle). Students performing Part A (bottom).

2. Before you use this apparatus: What do you expect will happen when you fill the tube with water to the height of the first large hole (from the bottom) and release your finger from the exit hole? Explain your expectations in terms of the forces acting on the fluid. What do you expect will happen when the water height above the exit hole is increased? Why?
3. Test your predictions. Begin by removing the rubber stopper from the lowest large hole. Simultaneously, hold your finger over the small exit hole, and fill the pipe with water until it runs out the hole the stopper was in. (*Think:* Why do we want to maintain a fixed water level within the tube?) Using a ruler, measure the height of the water column above the exit hole. Then, remove your finger from the exit hole letting the water run out, while you continually fill the pipe with water to maintain the same height of water column above the exit hole. Note how far the water squirts when it first strikes the ruler. Replace the stopper and repeat the steps for the next four holes, working up one hole at a time.
4. Plot the distance at which the water hit the ruler as a function of the height of the water column for each of the holes. Are the data consistent with your prediction in Step 2?
5. Would the distance that the water travels, for any given hole, change if the holes were bigger? Why?

### *Part B*

1. Take the second pipe (with three holes of different diameters), cover all three holes with your finger(s), and fill the pipe with water. Place the ruler perpendicular to the bottom of the pipe. Uncover one hole at a time and measure the distance at which the water first strikes the ruler. Does your observation agree with your reasoning in Step 5 above (Part A)?

This activity can be further developed to illustrate the concept of a reservoir (a large storage pool with inputs and outputs whose level [volume] changes depending on the difference between the inputs and outputs of water).

## Explanation

### *Part A*

The weight of the water column exerts pressure on the water at the level of the exit hole (imagine a cross-sectional area of the tube at the level of the hole). This pressure is higher compared to the pressure outside the hole (the atmospheric pressure), causing water to squirt out once the finger has been removed. As the height of the water column above the exit hole increases, the pressure difference between the inside and the outside of the exit hole increases, causing the water to squirt out to a greater distance. Recall that hydrostatic pressure is proportional to the height of the water column above the hole (the contribution of air pressure is the same on both sides of the hole).

### *Part B*

Except for very small holes (where friction becomes important), the size of the hole will not change significantly the distance to which the water travels. One way to solve this problem mathematically (for the more advanced students) is to consider pressure ($P = \rho gz$) as the potential energy ($PE = mgz$, where $m$ is the mass) per unit volume, $V$. Thus, $PE/V = mgz/V = \rho gz$. As a parcel of water squirts out of the column, most of its energy is transformed to kinetic energy ($KE/V = \rho v^2/2$, where $v$ is the velocity perpendicular to the hole). From conservation of energy, $\rho v^2/2 = \rho gz$, thus $v = \sqrt{2gz}$, that is, the velocity and hence the distance a given fluid travels does not depend on the size of the hole and is only a function of the height of the column ($z$).

The distance to which the fluid squirts can be predicted from a simple argument familiar to students with a background in mechanics. The fluid will arrive at the ground at $t = \sqrt{2H/g}$ seconds after leaving the hole, where $H$ is the height of the hole above ground, and at distance $L = vt$, where $v = \sqrt{2gz}$. In practice, the distance is decreased some, compared to the calculated distance, due to friction with the sides of the hole and with the air that the fluid travels through before arriving at the ground.

## 2.4. MANOMETER AND EQUILIBRIUM TUBES (Figure 2.4)

### Materials

- U-shaped manometer (made of supplies that can be found at any hardware store: clear plastic tube cut into three pieces and two elbows to connect the pieces of tube)
- Water
- Oil
- Equilibrium tube #1: arms of different *shapes* (https://www.eiscolabs.com/products/ph0202c and found on Amazon)
- Equilibrium tube #2: arms of different *diameters* (https://www.eiscolabs.com/products/ph0200b and found on Amazon)

### Instructions to the Students

Prior to these activities, the students have reviewed Newton's Second Law, which, when applied to fluids, implies that in the absence of other forces, fluid will flow from high to low pressure.

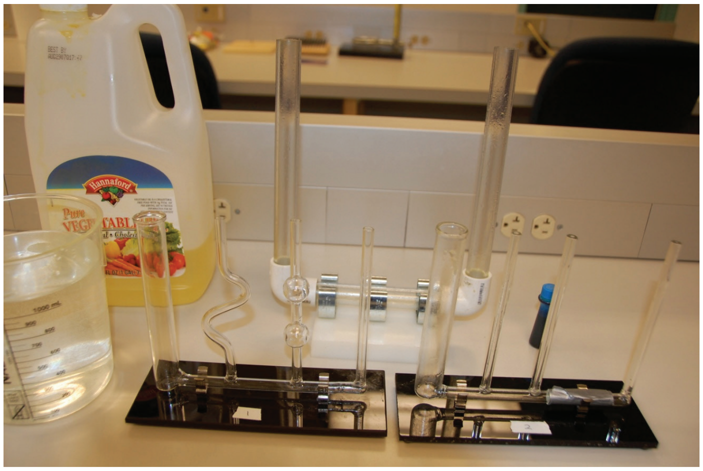

Figure 2.4. Materials used in Activity 2.4. The U-shaped manometer (Part A) is seen in the background. In the foreground is an equilibrium tube with different-shaped arms (left) and equilibrium tube with different arm diameters (right).

### Part A

1. Predict what will happen when you fill the U-shaped manometer with water. How will the water level compare between the two arms? Why? Sketch the manometer in cross section, showing your prediction, and explain your reasoning. (*Hint*: If the water is at rest [no flow along the tube], what can you say about the difference in pressure between the bottoms of each arm?) Fill the manometer until you can clearly see the waterline in each arm, and compare what you observe with your prediction.
2. What do you think will happen to the fluid level in each arm if you add oil (enough to form a layer of approximately 5 cm) to one arm? Why? If you predict a change, draw a qualitative diagram of the new equilibrium.
3. Add oil. Does your observation agree with your prediction? Explain.

### Part B

1. Study the equilibrium tube with different-shaped arms. Predict what the water level will be in each arm (relative to the other arms) when you partially fill the apparatus with water. Draw a qualitative diagram of your prediction and explain your reasoning.
2. Test your prediction.
3. Does your observation agree with your prediction? If not, how would you revise your explanation?

### Part C

1. Study the equilibrium tube with different arm diameters. Predict what the water level will be in each arm (relative to each other) when you fill the apparatus with water. Draw a qualitative diagram of your prediction and explain your reasoning.
2. Test your prediction.
3. Does your observation agree with your prediction? If not, how would you revise your explanation?

## Explanation

### Part A

A manometer is a device that measures pressure based on the fluid height. The simplest form of a manometer is a U-shaped tube filled with a fluid. The level of the water in each arm of the manometer is determined by the pressure that the air column plus the water column exert on the bottom of the arm. When one arm of the manometer is filled, water flows into the other arm until the system reaches equilibrium and there is no flow in the manometer, meaning that the pressure at the bottom of both tubes is equal ($P_1 = P_2$ and $P_1 = g\rho_{water} z_1 + P_{air}$; $P_2 = g\rho_{water} z_2 + P_{air}$, thus $z_1 = z_2$). The height of the water column in each arm will be the same. When oil is added atop the water in one arm, the manometer reaches a new equilibrium: $P_1 = P_2$ with $P_1 = g(\rho_{water} z_{water1} + \rho_{oil} z_{oil})$ and $P_2 = g\rho_{water} z_{water2}$. Because $\rho_{oil} < \rho_{water}$, the fluid column in the arm with water and oil must be higher than that in the arm with only water (air pressure being equal in both).

This activity can be used as an analogy to the dynamic height approach of calculating ocean surface slopes and for examining the relationship between integrated density and the height of a water column. The bottom of the U-shaped apparatus is analogous to the reference level of no water motion. At any height above the oil-water transition, there is a pressure difference between the two arms of the apparatus (hence, if we connected the arms above the bottom, fluid would flow from the arm containing oil + water to the arm containing water only until the system reaches a new equilibrium).

### Part B

The shape or cross-sectional area of the arm(s) of a manometer has no effect on the water level. The height of the water (or any other fluid) column in each arm is a function of the pressure and the density of the fluid ($z = P/\rho g$). Thus, after the fluid is introduced to the column and the system reaches equilibrium, the pressure at the bottom of each arm is equal (no flow) and the height of the water will be the same for each arm, regardless of its shape. This observation explains why the pressure at a given depth is the same pressure whether in a pool or in a lake (assuming atmospheric pressure above the pool and the lake is the same).

*Part C*

The same principle applies to the equilibrium tube with arms of varying diameters. The height of the water column will be the same for each arm. The only exception to this statement involves the thinnest arm of equilibrium tube #2, for which another force becomes important; surface tension at the rim of the glass acts to pull the water to a higher level (this observation can be used as a brainteaser, leading to another class focused on surface tension and capillary action).

## 2.5. SHRINKING BALLOONS (Figure 2.5)

### Materials

- Vacuum container used for food preservation (found in kitchen-appliance stores)
- Pressure apparatus (2-liter soda bottle fitted with a hand pump that is used for keeping soda bottles carbonated and can be found in many grocery stores)
- Two balloons of the same size (one filled with air, the other with water)
- Marshmallows (Peeps are students' favorites) and any other items to be tested (e.g., tangerine, cherry tomato)

### Instructions to the Students

1. Predict what would be the effect of reduced pressure on each of the balloons.
2. Place the balloon filled with air in the vacuum container and evacuate the air from the container by using the hand pump. What happens to the balloon? Release the valve, allowing air to get back into the container. What happens to the balloon now?
3. Repeat this experiment with the balloon that is filled with water. Does the effect of pressure differ between the two balloons? Why?
4. Based on your observations, what do you think will happen to the marshmallow (and any other items to be tested) when you evacuate the container?
5. Test your prediction.
6. Release the valve and observe the marshmallow. Explain your observations.
7. Explore the second pressure apparatus. Compare/contrast your observations on the behavior of the balloon filled with air in this apparatus to the behavior of the balloon filled with air in the vacuum container. What is the difference between this apparatus and the vacuum chamber?


Figure 2.5. (top) Materials for Activity 2.5. (middle) Testing an air-filled vacuum container. (bottom) An air-filled balloon under atmospheric pressure (left) and after air was pumped into the bottle (pressure increased; right).

*A challenge*:

1. How would you get a balloon full of air into the soda bottle?
2. How could you use this apparatus to demonstrate that air has weight?

### Explanation

Objects that contain air cavities expand when the pressure around them decreases, as occurs when evacuating air from the vacuum container (Figure 2.5, top left panel). Because water is, to a large extent, an incompressible fluid, the size of the balloon containing water will be the same under low pressure and under atmospheric pressure. A cherry tomato will behave similar to the water balloon as it does not contain air pockets. A tangerine or a marshmallow, on the other hand, contains air pockets, and will expand when placed in a vacuum. When the valve is released, air rushes back into the container, increasing the pressure (until it reaches atmospheric pressure), and the tangerine and marshmallow will shrink, but not necessarily to their original sizes because the structure of the material has been altered in the process (e.g., merging of air cavities in the marshmallow).

When we pressurize the soda bottle by pumping air into it, the pressure around the balloon increases and it shrinks to a smaller volume (increasing its internal pressure—compare the bottom right and left panels of Figure 2.5). Releasing the pressure valve brings the air-filled balloon back to its original size.

*Challenge*: To insert an air-filled balloon into the bottle, place the opening of a balloon around the opening of the bottle, leaving a small space to insert a straw between the balloon and the wall of the bottle. As you blow into the balloon, air from the bottle can escape outside through the straw, allowing the balloon to expand. Tie a small knot and push the balloon inside the bottle. This apparatus can be also used to demonstrate that air has non-negligible mass by weighing the bottle at atmospheric pressure, then pumping air into the bottle and weighing it again (the mass is retrieved by dividing by *g*, automatically done by computer chips within balances).

## 2.6. COMPRESSIBILITY OF GASES (Figure 2.6)

### Materials

- Compressibility of gases apparatus (Arbor Scientific, or a homemade version can be easily assembled—a sealed 60-ml syringe has a cross section of 1 in$^2$)
- Weights of known mass (we use 2.5-lb barbell weights)

### Instructions to the Students

1. Record the volume of air in the syringe under conditions of atmospheric pressure.
2. What do you think the volume of air in the syringe will be if you place 2.5 lbs on top of the apparatus? What is the pressure within the syringe?
3. What will happen to the volume of the air in the syringe if you keep adding weights? By what percentage will it change by the time you place 15 lbs on top of the syringe?
4. Test your predictions. Place a weight on the top of the syringe (2.5 lbs) and record the volume of air. Place additional weights (totaling 5 lbs, 10 lbs, and 15 lbs) and record the change in air volume for each added mass. What do you observe?
5. Plot the added mass vs. the volume of air in the syringe. How does the volume depend on the added mass? Does it agree with your predictions? Do you feel a change in temperature as you compress the air? Should you expect one?
6. By what percentage did the pressure increase in the syringe, compared to the atmospheric pressure (the pressure applied by a mass of 14.7 lbs on a square inch at Earth's surface), when all the weights were placed on the syringe (15 lbs; noting that the cross section of the syringe is ~ 1 in$^2$)? By what percentage did the volume of the syringe change when the 15 lbs of weight were added (assuming no change in temperature)?

Figure 2.6. (top) Materials for Activity 2.6. (bottom) The apparatus once 15 lbs have been laid on its top.

7. Using your data, how do you expect the volume of the lungs of a free diver to change when diving to 10 m? (Pressure increases by one atmosphere every 10 m).

*Note*: It is difficult to find metric-system weights appropriate for this set up. This activity can provide an opportunity to practice unit conversion.

### Explanation

In this activity, under normal atmospheric pressure, the volume of air in the syringe is 46 ml. For an ideal gas at constant temperature, $T$, the volume, $V$, of the gas varies inversely to the pressure applied to the gas (Boyle's Law: under constant temperature conditions the product of the pressure, $P$, and volume of a gas, $V$, is constant $\rightarrow PV = \text{constant}$ and $P = \text{constant}/V$). Thus, the addition of weights (increase in pressure) will reduce the volume of air in the syringe. Adding 15 lbs of mass to the syringe approximately doubles the pressure (compared to normal atmospheric pressure), and the volume of air in the syringe decreases by half, as expected from Boyle's Law. Similarly, when a free diver dives to a depth of 10 m, the pressure he/she experiences doubles relative to what it is at the surface. As a result, the volume of his/hers lungs will be reduced by half. Although we expect the gas in the syringe to heat up as it is compressed, exchanges in temperature with the room result in little or no perceptible change; hence, the assumption of constant temperature is valid. This activity demonstrates well the weight of the atmosphere, a weight we are mostly unaware of in everyday life.

## ACTIVITY 2.7

To demonstrate Bernoulli's Principle, we hand the students a long plastic bag (Bernoulli bag; Arbor Scientific; Figure 2.7). We ask one student to hold the open end of the bag and another student to hold the closed end, so that it is held horizontal, parallel to the floor. We then ask the students if they can fill the bag with only one gust of air. The tendency of most students is to seal the bag against their lips and blow air into it repeatedly, requiring many breaths (Figure 2.7, top panel). A much more effective technique is to blow into the opening of the bag from a distance (Figure 2.7, bottom panel), which creates a low-pressure area near the opening where velocity is high. This local low pressure brings in air from the surrounding atmosphere (where the pressure is higher), and all the air flows rapidly into the bag. The bag is not elastic and provides little resistance to the gushing air (as long as it is not full).

Figure 2.7. (top) A student attempting to fill the bag while holding the bag against the lips. (bottom) When keeping the opening of the bag wide open and blowing from distance toward the opening, the bag can be filled with only one gust of air.

## REFERENCES AND OTHER RECOMMENDED READING


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Faber, T.E. 1995. Chapter 1 in *Fluid Dynamics for Physicists*, Cambridge University Press.

Hewitt, P.G. 2008. Chapter 7 in *Conceptual Physics Fundamentals*. Addison Wesley.

Richardson, D., ed. 2005. *The Encyclopedia of Recreational Diving*, 3rd ed. PADI, Santa Margarita, CA.

Vogel, S. 1996. Chapters 3 and 4 in *Life in Moving Fluids*. Princeton University Press, Princeton, NJ, 484 pp.


## OTHER RESOURCES


Sorbjan, Z. 1996. *Hands-On Meteorology: Stories, Theories, and Simple Experiments*. American Meteorological Society, Washington, DC. A collection of hands-on experiments designed around concepts of meteorology. Chapter 3 addresses pressure. In addition to the experiments, the book contains historical narratives, references to important discoveries, and some stories about famous and infamous scientists.

A YouTube movie containing a series of demonstrations of Bernoulli's principle by Julius Sumner Miller – Physics – Bernoulli: https://www.youtube.com/watch?v=7XHohWDIUB0

# DISCREPANT EVENTS: AWAKENING STUDENTS' CURIOSITY

To attract students' attention, provoke thought, and initiate inquiry, educators sometimes use *discrepant events* (Hassard, 2005; Chiapetta and Koballa, 2006). Such events present surprises, causing students to wonder, "What's going on?" An example of a discrepant event is Activity 2.2. Students feel that the smaller ball is "heavier," but after measuring the mass of each ball they are surprised to discover that the larger ball is the heavier of the two. That finding causes them to rethink the concepts of pressure and weight and helps them to differentiate between force and pressure (force per unit area). Compendia of discrepant events related to various science concepts are readily available on the Internet and in science teaching texts. For example, Liem (1987) has compiled over 400 discrepant events that use simple materials—with sketches, questions, and explanations—for the science teaching of elementary through college students.

An effective discrepant event often requires very little instruction. For example, at the start of class, an instructor may silently fill an empty, transparent 2-liter soda bottle one-quarter of the way with very hot water, swirl the water around for a few seconds to warm the whole bottle, pour the water out of the bottle, screw the cap on tightly, and then set the bottle in full view of the students. While the instructor takes roll, the bottle crumples inward in several places. Invariably, the students become intrigued and start asking questions about the bottle and the water. The instructor can guide the dynamics of the students' questioning and hypothesizing as to the explanation of the bottle's collapse, leading to a discussion of the Ideal Gas Law and the relationship between temperature, pressure, and volume.

Presenting students with a puzzle in the form of an unexpected event challenges their preconceptions, whether based on knowledge or intuition, triggers curiosity, and increases motivation to find a solution. Through the process of inquiry, leading to discovery, students can reach new levels of cognitive understanding and develop better problem-solving skills (Piaget, 1971). Discrepant events need not be physical activities; they may be presented through films, descriptions of events, or field observations (e.g., reversed magnetism in rocks) that present intriguing paradoxes. Discrepant events can be used to achieve specific pedagogical goals—initiating a lesson and getting students' attention, eliciting questions from students, identifying and addressing students' misconceptions, causing students to continue thinking about a process or a problem after the end of a lesson, testing whether students can apply what they have learned to explain a similar, but unexpected phenomenon, and serving as a part of a formal lesson evaluation. Whenever a discrepant event is presented, it is important to allow students sufficient time to think about, discuss, and try to explain the event.

## REFERENCES

Chiappetta, E.L., and T.R. Koballa Jr. 2006. *Science Instruction in the Middle and Secondary Schools: Developing Fundamental Knowledge and Skills for Teaching*, 3rd ed. Pearson/Merrill Prentice Hall, Upper Saddle River, NJ, 320 pp.

Hassard, J. 2005. *The Art of Teaching Science*. Oxford University Press, 496 pp.

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# CHAPTER 3. BUOYANCY

## PURPOSE OF ACTIVITIES

This set of activities was designed to help students better understand the underlying principles of buoyancy. Most students have heard the term *buoyancy* and have experienced it when entering the ocean, a pool, or a bath. Some may even be able to recite Archimedes' Principle. However, our experience has shown that students often struggle when asked to address questions related to buoyancy. Research conducted at the University of Washington found that many science and engineering majors lacked an understanding of buoyancy even after taking introductory physics classes that taught hydrostatics (by a standard instructional approach) and were not able to predict or explain the floating and sinking behaviors of different objects (Loverude et al., 2003).

We introduce buoyancy to our students after they have already completed the labs on density (Chapter 1) and pressure (Chapter 2). In the density lesson, students examined sinking and floating behaviors of various objects as a function of their densities, but did not investigate the underlying principles governing these behaviors. The activities below allow students to apply knowledge gained in the previous two lessons to further explore the factors governing sinking and floating.

## BACKGROUND

When an object is immersed in a fluid, the fluid is displaced to "make room" for the object. For example, when you get into a bathtub, the water level rises. The amount of water an object displaces when fully submerged is equal to its own volume (e.g., recall the measurements of rock volume in Activity 1.3). The immersed object is subjected to two forces: (1) a downward force—the ***gravity force,*** which increases as the mass of the object increases, and (2) an upward force—the ***buoyancy force,*** which increases as the density of the fluid increases. When the downward gravitational force on an object is greater than the upward buoyancy force, the object sinks; otherwise, the object floats.

The buoyant force arises from an imbalance in the pressures exerted on the object by the fluid. Because pressure increases with depth, the bottom of the immersed object experiences a higher pressure than does its top; therefore, the object experiences an upward force. The resulting upward force equals the weight of the displaced fluid (Archimedes' Principle). If the weight of an object (in air) is greater than the weight of the displaced fluid, it will sink; if it is less, it will float.

In mathematical terms, the two opposing forces can be written (based on Newton's Second Law) as

$$F_{bouyancy} = m_{fluid}\,g = \rho_{fluid}V_{displaced}\,g$$

and

$$F_{gravity} = m_{object}\,g = \rho_{object}V_{object}\,g.$$

Where $m_{fluid}$ and $m_{object}$ are the masses of the displaced fluid and the object, $g$ is the gravitational acceleration constant, $\rho_{fluid}$ and $\rho_{object}$ are the densities of the fluid and the object, and $V_{displaced}$ and $V_{object}$ are the volumes of the displaced water and the object. When the object is fully immersed, $V_{displaced} = V_{object}$. From the definition of density, recall $m = \rho V$.

The difference between the two forces determines whether the body sinks, floats, or remains neutrally buoyant.

$$\Delta F = F_{gravity} - F_{bouyancy} = V_{object}\,g\,(\rho_{object} - \rho_{fluid})$$

When $\Delta F > 0$, the object sinks. When $\Delta F < 0$, the object floats. And when $\Delta F = 0$, the object remains at its depth (it is neutrally buoyant; that is, $\rho_{object} = \rho_{fluid}$). So, the key to keeping a ship afloat, whether it is made of wood, steel, or concrete, is to have it displace a volume of water that weighs more than the ship itself.

### Applications to the Ocean

Buoyancy is one of four dominant forces in ocean dynamics (the other three are gravity, wind stress, and friction), and understanding buoyancy is key for understanding density-driven circulation. The ocean's large-scale thermohaline circulation, for example, is attributed to latitudinal differences in buoyancy forcing, due to high-latitude versus low-latitude differences in water temperature. Cooling and evaporation make seawater denser, so surface waters subjected to these conditions become less buoyant, tending to sink. Warming and precipitation, in contrast, decrease seawater density, so surface waters subjected to these conditions become more buoyant, tending to float at the ocean's surface.

The level at which an object floats in a liquid (e.g., seawater or magma) depends on the balance between the gravitational and buoyancy forces to which the object is subjected. Earth's lithospheric plates, for example, float on the asthenosphere (the upper mantle) at an equilibrium level (a buoyancy equilibrium called "isostasy"). When a buoyant equilibrium is disrupted, the object will sink or rise until a new buoyancy equilibrium is reached. This process is termed "isostatic leveling." The effects of isostatic leveling can be seen near mid-ocean ridges where freshly formed lithosphere is cooling and adding weight to the underlying ridge (the gravity force has increased) and on continental plates where large glaciers have recently melted (the gravity force has decreased). Changes in the buoyancy equilibrium of lithospheric plates will cause a relative rise or fall in sea level along the coast associated with the plate.

Many marine organisms face the challenge of buoyancy regulation. Proteins, connective tissues, skeletons, and shells all have densities greater than the density of seawater. Organisms with high body density may sink below their optimal growth zone (e.g., phytoplankton sinking below the photic zone) and be exposed to changes in pressure, light, and temperature. In response to these challenges, marine organisms have developed a variety of strategies to control their buoyancy. Examples include the selective exchange of heavier ions for lighter ions, storage of fat and lipids, and the use of gas-filled cavities.

Buoyancy is also a fundamental principle in the design of boats, ships, submarines, and autonomous underwater vehicles (AUVs), with the latter being the state-of-the-art in ocean technology and exploration. Autonomous gliders and floats, which carry a variety of sensors (e.g., temperature, salinity, and optical), move up and down in the water column by changing their volume and thus the buoyancy force acting on them. The principle of operation is the exchanges of fluid between an internal incompressible tank and an external inflatable bladder. For an illustration of a float that uses this mode of buoyancy regulation, visit: https://argo.ucsd.edu/about/.

## DESCRIPTION OF ACTIVITIES

We begin the lesson with a short introduction or review of the forces that act on an immersed object, after which students engage in the activities below, working in small groups. Two of the activities (3.1 and 3.2) are quantitative representations of Archimedes' Principle, allowing students to explore the relationships among the mass of an object, the mass of the volume it displaces (proportional to the buoyancy force), and its sinking or floating behavior. We ask students to conduct both activities (the order does not matter). By doing this, we can reinforce the principles of buoyancy, allow students to practice transfer of knowledge learned in one situation to another, and test their understanding. The two other activities (3.3 and 3.4) are what we term "open inquiry": students are not provided with much instruction and are expected to synthesize and apply knowledge learned in the previous lessons on density and pressure (Chapters 1 and 2 in this document) to explain a given phenomenon and construct a float. Applications to the aquatic environment are discussed during the review and discussion session at the lesson's end. The activities are set up at stations as described in Chapter 1.

## ACTIVITY 3.1. MAYDAY! (Figure 3.1)

### Materials

- Archimedes' box (a box with horizontal gradation marks every 1 cm, https://www.wardsci.com/store/product/8866766/archimedes-block-model)
- Spring scale
- 5-g and 10-g weights
- Container with water
- Ring stand
- Ruler
- Balance

*Note:* The special box, spring scale, and weights were all obtained from https://www.wardsci.com/store/.

### Instructions to the Students

1. Assume that the box is a cargo ship. As a crew member, you need to determine the maximum cargo weight (in grams) that you can load on your ship without sinking it. At the point of maximum loading, the box (your ship) will be fully—but just barely—submerged, so that its top just touches the water's surface. Based on what you know about buoyancy and Archimedes' Principle, how would you determine the maximum amount of cargo? Explain your rationale. (*Hint*: Think about the weight of an object in air and in water [fully immersed] and the volume it displaces. Use the spring scale and ruler to obtain any measurements that can help with your prediction. To use the spring scale, attach it to the ring stand and use the hook to hold the box).
2. Add the predicted maximum amount of cargo to your box (ship), close the lid, and test your prediction by placing the loaded ship in the tub of water and observing whether it is fully immersed but not sinking.
3. If your prediction was correct, what is the mass of the ship + cargo in air? What is the mass of the ship + cargo in water? What are the volume and mass of the water that was displaced?

4. If your prediction was not correct (i.e., if your boat sank or floated above the water's surface), revise your prediction and test it again.
5. Once you find the maximum allowable cargo weight, add an additional 25 g to your cargo and place the box in the water. What happens to your ship now? Why?
6. What is the new weight of the ship + cargo in air? Predict the weight of the ship + cargo in water. Use the spring scale to measure the weight of the ship + cargo in water. Does your measurement agree with your prediction?
7. What is the weight of the water that is displaced? How does it compare to the weight of the ship + cargo in air and the weight of the ship + cargo in water?
8. Can you now explain why an object submerged in water "feels" lighter?

*Note to instructors*: If your students struggle to predict the amount of maximum cargo based on Archimedes' Principle, then suggest that they approach the problem using the following few steps:

1. Measure and compute the mass and volume of the box without the weights. Add weights in increments of 25 g. With each addition, measure:
   a. The weight of the box outside the water (using the spring scale)
   b. The weight of the box in the water
   c. The height of the section of the box that is immersed in water (each mark on the box is 1cm)

   For each increment, calculate the volume of water displaced by the box.
2. Plot the height of the box section immersed in water as a function of the weight of the box + added weights. Do you see any pattern between the mass of the box + weights (in air) and the volume displaced? What is the weight of the box *in water* in each case?

Once the students complete these steps, have them do Steps 3–4 above.

## Explanation

The box we use for this activity has a 5 cm x 5 cm = 25 cm$^2$ base and a height of 4 cm. Thus, its volume is 100 cm$^3$ (including its lid). The empty box weighs 25 g; hence, its density is 0.25 g/cm$^3$. When the box is fully submerged, it displaces its volume (100 cm$^3$); therefore, the weight of the displaced water is 100 g (1 cm$^3$ ≈ 1 g). According to Archimedes' Principle, when the box is neither sinking nor rising, $F_{buoyancy} = F_{gravity}$, where $F_{buoyancy} = \rho_{water} V_{displaced} g$. Because $\rho_{water}$ and $g$ are constant in this case, $F_{buoyancy}$ is proportional to the displaced volume. The maximum mass that can be added to the box without sinking it is 75 g ($m_{box} + m_{weights}$= 25 g + 75 g = 100 g). When the box barely floats, $F_{gravity}$ is equal to $F_{buoyancy}$ (recall $F_{gravity} = mg$).

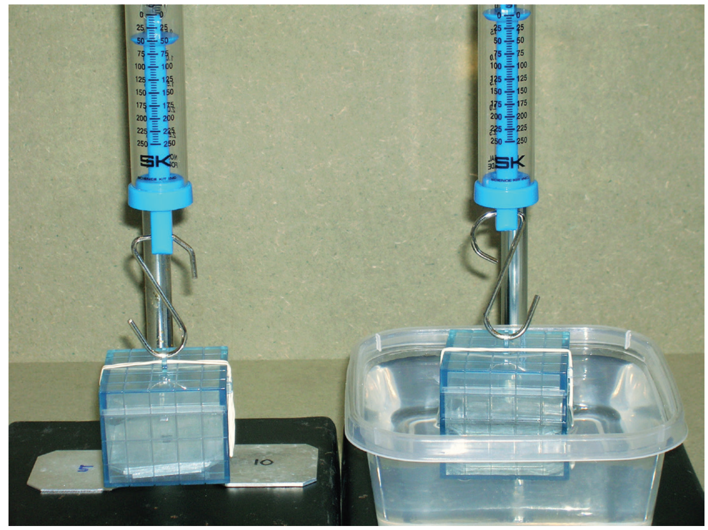

Figure 3.1. Apparatus for Activity 3.1 in air (left, with two weights lying on the table) and in water (right). From https://www.wardsci.com/store/product/8866766/archimedes-block-model.

When students conduct this activity in small steps, by adding mass in increments of 25 g, they can closely examine the relationship between the mass of an object in air, the displacement of water (immersion depth), and the apparent mass of the object in water, as shown in the table below.

| Added mass (g) | Total weight in air (box + weights) (g) | Weight in water (g) | Immersion depth (cm) | Displaced volume (cm$^3$) |
|---|---|---|---|---|
| 0 | 25 | 0 | 1 | 25 |
| 25 | 50 | 0 | 2 | 50 |
| 50 | 75 | 0 | 3 | 75 |
| 75 | 100 | 0 | 4 | 100 |

By Archimedes' Principle, the box sinks when its weight exceeds that of the displaced water. Thus, when an additional 25 g is added to bring the total mass of the box + weights in air to 125 g, which is larger than the mass of the volume displaced (100 g), the "ship" sinks. The weight of the box + weights in water is 25 g, which is proportional to the difference between the gravitational and buoyant forces.

Because $g$ is constant, we consider only the masses of the box and the displaced water, but we emphasize to the students that mass and weight should not be confused (weight = $mg$). It is also important to explicitly discuss with students the difference between the case of a floating object and the case of a submerged object. In both cases, the magnitude of the buoyant force equals the mass of the water displaced. However, for a floating object, the volume that is displaced (the buoyant force) is determined by the ***weight*** of the object divided by the density of the fluid; for a fully submerged object, the volume displaced is determined by the ***volume*** of the object (density does not play a role).

## ACTIVITY 3.2. ARCHIMEDES BALL (Figure 3.2)

### Materials

- Archimedes ball (can be found on Ali Express, searching for "Submarine Sinking and Floating Principle")
- 60-ml syringe
- Piece of tubing
- Scale
- Caliper
- Container with water
- Container with a sugar solution, labeled "unknown liquid"

### Instructions to the Students

1. Imagine that the plastic ball is a submarine. You want it to remain under water such that the stopper only is just above the water surface (i.e., the submarine is neutrally buoyant). Calculate how much ballast water do you need to add to the submarine so that it is neutrally buoyant? (*Hint*: If you are not sure where to begin, draw the submarine and the forces acting on it when it is immersed in water).
2. Check your prediction (calculation) by placing the ball in a container of water and drawing in freshwater, using the syringe. The markings on the syringe will indicate how much water is being added to the ball. Does the volume that you obtained experimentally agree with your calculations?

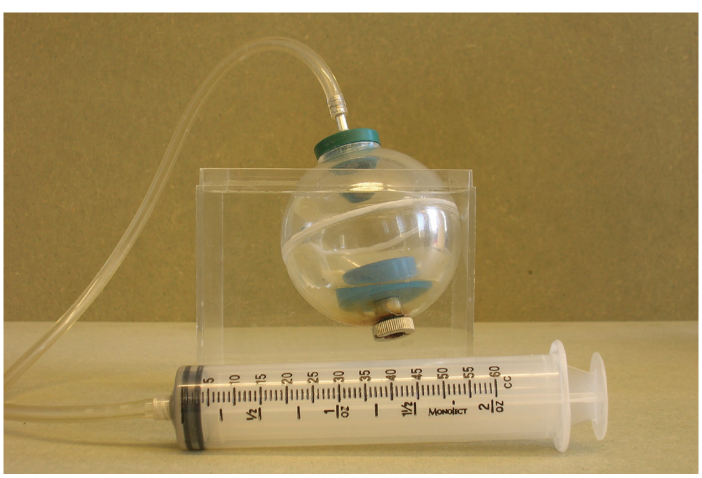

Figure 3.2. Apparatus for Activity 3.2. (can be found on Ali Express, searching for "Submarine Sinking and Floating Principle")

3. Place your "submarine" in the "unknown liquid" and draw in the unknown liquid until the submarine is neutrally buoyant. Based on the volume of the unknown ballast liquid that you needed to draw in, how do you think the density of the unknown liquid compares to that of freshwater?

### Explanation

The ball we use for this activity has a density of 0.7 $g/cm^3$, which is less than the density of water (1 $g/cm^3$); hence, the ball floats. Because the ball's volume remains constant, the only way to make this "submarine" neutrally buoyant (fully submerged) is to add mass by pulling out air (with the syringe) and replacing it with water. The mass of the ball is 124.5 g and its volume is 176 $cm^3$. When the ball is fully submerged, it displaces 176 ml ($cm^3$) of water that weighs 176 g. Therefore, approximately 52 g (about 52 ml) of tap water must be added to make the ball's density equal to that of water (i.e., to make the ball neutrally buoyant). When students put the ball in the "unknown liquid," they find that a larger volume of water is required to achieve neutral buoyancy, indicating that the unknown solution (e.g., sugar water) is denser than freshwater, increasing the buoyant force acting on the sub.

## ACTIVITY 3.3. DESIGNING FLOATS (Figure 3.3)

### Materials

- Containers with freshwater and salt solution
- Two beakers or deep tubs
- Film canisters or small vials
- Weights (washers, pennies, etc.)
- Additional miscellaneous supplies: balloons, rubber bands, tape, drinking straws, plastic aquarium tubing, glue guns and glue, paper clips, duct tape, bubble wrap, pipe cleaners, syringes, corks, packing peanuts (you don't need everything; these are only examples)
- Scale
- Caliper or ruler
- Graduated cylinder
- Aquarium with stratified fluid (saltwater and freshwater)

*Note*: The salt solution in the aquarium should be the same as in the container of saltwater mentioned at the top of the list.

### Instructions to the Students

You are funded to design two autonomous floats that will carry sensors (washers) to measure various hydrographic properties (e.g., temperature, salinity) and biogeochemical properties (e.g., oxygen, chlorophyll fluorescence, turbidity) in the Gulf


Figure 3.3. A student testing Activity 3.3 "floats" in a stratified tank.

of Maine. One float should be able to drift at the surface. It should float such that the top of the cap is just above the water surface. The other should float at the pycnocline (the location where the density changes the most) without touching the bottom of the tank.

Your first goal is to design a prototype of the floats, as a proof of concept, to be presented to your program managers (classmates). You have at your disposal a bucket with surface water (freshwater) and one with deep water (salt solution). In your presentation, describe the design of your floats and your approach for determining their sinking and floating behaviors. At the end of the class, you will be asked to demonstrate that indeed one of your prototypes remains at the surface while the other hovers at the pycnocline in a stratified tank.

## Explanation

We use this activity to add a healthy competitive component to the lesson. From our experience, most students first approach this problem by trial and error. We therefore encourage them, using probing questions, to approach it using Archimedes' Principle. At the end of the lesson, as part of the group discussion, each team tests the floats in a large aquarium with a stratified water column. (Be sure to use the same saltwater solution that the students used in their containers.)

# ACTIVITY 3.4. CARTESIAN DIVER (Figure 3.4)

*This classic science experiment is named after René Descartes, a French philosopher, mathematician, and scientist. It demonstrates buoyancy (Archimedes' Principle) and the relationship between pressure and volume in gases (Ideal Gas Law).*

## Materials

- A sealed soda bottle filled with tap water (colored water works best)
- A plastic pipette weighted with metal nuts and/or washers

*Note:* For instructions on how to build a Cartesian diver, see, for example, https://www.fizzicseducation.com.au/150-science-experiments/force-movement-experiments/make-a-cartesian-diver/.

## Instructions to the Students

1. Squeeze the bottle. Why is the half-closed pipette inside the bottle sinking? Why does the pipette rise when you release the bottle?
2. Explain the behavior of the pipette in terms of pressure and Archimedes' Principle.

## Explanation

According to Pascal's Law, pressure applied to a fluid is transmitted throughout the fluid. When you squeeze the bottle, you increase the pressure within the bottle and the open pipette within it. The pipette in the bottle contains air. As a result of

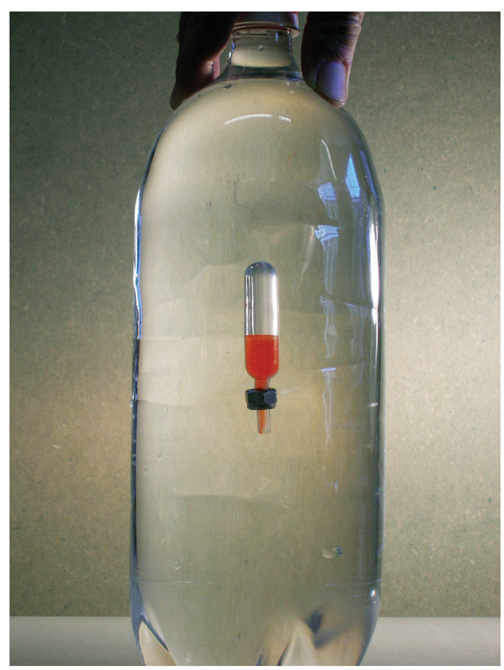

Figure 3.4. A Cartesian diver.

the increase in pressure, the volume of the air trapped inside the pipette decreases and water rises within the pipette, replacing some of the air space. (Recall the Ideal Gas Law: $PV = nRT$, where $P$ is pressure, $V$ is volume, $n$ is the number of moles of gas, and $R$ is the universal gas constant. For constant temperature, increasing pressure results in decreasing volume.) Because the density of water is greater than that of air, the density of the pipette system (pipette + air bubble + water) increases enough that the pipette sinks.

## SUPPLEMENTARY ACTIVITY (Figure 3.5)

For assessment, we administer a quiz (see p. 31) on concepts covered in this lesson and the previous ones on density and pressure as well as a problem-solving challenge. For the challenge, we present students with a well-known question: "*You have a large rock on a boat floating in a pond. When you throw the rock overboard and it sinks, will the level of the pond rise, drop, or remain the same?*"

To solve this problem, one ought to compare the volume of water displaced due to the rock is in the boat ($V_{displaced\_b}$) to the volume displaced when the rock is fully submerged ($V_{displaced\_s}$). Which is greater? Considering first the case of the rock in the boat, by Archimedes' Principle, that the weight of the rock (neither rising nor sinking) equals the weight of the displaced water: $m_{object}\, g = m_{displaced\_b}\, g$. Also, from the definition of density, $m_{object} = \rho_{object} V_{object}$, $m_{displaced} = \rho_{fluid} V_{displaced}$. Combining these two bits of information yields the volume displaced when the rock is in the boat: $V_{displaced\_b} = V_{object}\, \rho_{object} / \rho_{fluid}$. Considering now the case of the submerged rock, this volume of displaced water is equal to the rock's own volume: $V_{displaced\_s} = V_{object}$. Finally, to predict what happens to the water level when we toss the rock overboard, the two displacement volumes are compared by looking at their ratio: $V_{displaced\_b} / V_{displaced\_s} = \rho_{object} / \rho_{fluid}$. Because the rock sinks in water, we know that $\rho_{object} > \rho_{fluid}$, which tells us that $V_{displaced\_b} > V_{displaced\_s}$: the volume of water displaced by the rock in the boat is larger than the volume displaced by the submerged rock. Thus, when you throw the rock overboard, the pond's water level will drop. *Note*: the volume of water displaced due to the boat's own weight is the same whether the rock is in it or not and hence plays no role.

We first give students a few minutes to think individually about the problem, then ask them to vote on whether they think the water level will rise, drop, or remain the same. We always get votes for each option. We then group the students according to their "vote." Each group must come up with an argument (physical explanation) that supports their prediction (or discover in the process that their prediction needs to be revised) and present it to the entire class.

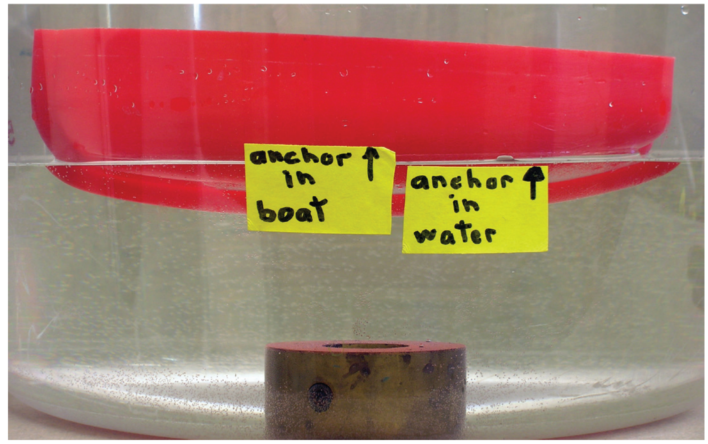


Figure 3.5. The water level when the weight is placed in the boat (labeled as "anchor in boat") and when the weight is submerged under water (labeled as "anchor in water").

After each group has presented, we test their predictions (you will need a child's toy boat, a weight or a large rock, and a tub filled with water). We place a child's toy boat in a clear tub filled with water and load it with a weight or a large rock. We ask a student to mark the water level in the tub, to drop the weight (rock) into the water, and then to mark the new water level (Figure 3.5).

With this kind of assessment, students do not feel the pressure of being "tested," yet they are forced to apply their knowledge, identify gaps in their understanding, and seek better explanations to fill these gaps. Instructor(s) move among groups as they form their explanations, assess the level of each student's involvement, and identify areas of difficulty. Any concepts identified as problematic are later reviewed during the demonstration. As an alternative assessment, we use the five-block problem described in Loverude et al. (2003).

## REFERENCES AND OTHER RECOMMENDED READING

Denny, M.W. 1995. Chapters 3 and 4 in *Air and Water*. Princeton University Press, Princeton, NJ.

Hewitt, P.G. 2008. Chapter 7 in *Conceptual Physics Fundamentals*. Pearson Addison-Wesley.

Loverude, M.E, C.H. Kautz, and P.R.I. Heron. 2003. Helping students develop an understanding of Archimedes' Principle. I. Research on student understanding. *American Journal of Physics* 71(1):178–1,187.

Vogel, S. 1996. Chapters 3 and 4 in *Life in Moving Fluids*. Princeton University Press, Princeton, NJ.

## OTHER RESOURCES

Sorbjan, Z. 1996. *Hands-On Meteorology: Stories, Theories, and Simple Experiments*. American Meteorological Society. Washington, DC. A collection of hands-on experiments designed around concepts of meteorology. Chapter 7 addresses buoyancy. In addition to experiments, the book contains historical narratives, references to important discoveries, and stories about famous and infamous scientists.

# ASSESSING STUDENT LEARNING

Assessing students' learning is an essential and sometimes challenging aspect of teaching. Pen-and-paper tests are a common form of assessment, though they tend to test more for memorization than for deeper understanding, synthesis, and application of knowledge. Pressured by administrations, society, and students themselves to provide grades, educators often fall back on simple forms of objective tests (e.g., multiple choice). However, test results may not reveal why students succeeded or failed. If the goal is to determine how well—not just how much—students are learning, then a case can be made for employing assessment procedures that reflect the full range of our educational goals (e.g., Fink, 2003). This is not to say that pen-and-paper tests don't have a place in formal education; we use essay exams and multiple-choice tests in our own classes. However, we maintain that a broader range of assessment methods should be considered and used to assess not only student learning but also our effectiveness as educators. These methods include both formal evaluation (e.g., research papers, laboratory activities, oral presentations, oral exams) and informal evaluation (e.g., observing students' behavior during class and their participation in discussions) (Hassard, 2005; Feller and Lotter, 2009). Our goal in this short essay is not to provide a comprehensive review of assessment tools or point out the best assessment practice. Rather, it is to share our experience and stimulate the reader to think about the value of assessment and how it can be used more effectively in the classroom to enhance learning. Practices should vary depending on learning goals, the number of students in class, their backgrounds, and the classroom setup. The reliability of assessment and evaluation may be increased by using several different methods to measure the same expected learning outcomes.

With very large classes, hands-on, inquiry-based activities and assessment methods other than multiple-choice or short-answer tests are more difficult to implement, but there are ways in which traditional assessments, such as multiple-choice tests, can become part of an active learning process. Following Fink (2003), we give students a weekly multiple-choice quiz and ask them to complete it initially as individuals. After collecting the individual quizzes, students are asked to retake the quiz, this time as a team of three to four students. The team has to reach consensus for each answer. For direct feedback, we give each team a prefabricated scratch-off answer sheet (similar to a lottery ticket; see https://www.cognalearn.com/ifat). Students scratch off the covering to reveal if the answer they chose is correct (showing a star) or incorrect (showing a blank square). In this process, students re-assess their understanding and are encouraged to communicate their ideas in a less stressful, more collaborative environment. We tend to keep the same teams throughout the semester. To foster healthy competition, we record the number of points each team earns per week (based on the number of correct answers), and the winning team is awarded a pizza party at the end of the semester.

Another tool we use is a reflective journal in which students assess their own learning. We first tried the traditional approach, using a lab notebook as a journal, but students did not respond well; the journals became a collection of information and facts rather than a reflection on learning. Students responded very well, however, when we switched to Web-based blogs. Each student creates a blog (e.g., on https://www.blogger.com/), a medium that proved to be more comfortable and familiar. Each week, students respond to guiding questions that prompt them to comment on new concepts they have learned, identify weaknesses in their understanding, raise questions, and identify aspects of the lesson that were and were not useful. Only instructors have access to the blogs, or they provide weekly feedback to each student. Reflective blogs provide instructors with immediate feedback that can be used to align instructional strategies and expected learning outcomes with student understanding. Blogging encourages students to think critically about the material after each lesson and provides a means to assess their understanding on a regular basis rather than only at the course's end.

## RECOMMENDED READING


Hassard, J. 2005. *The Art of Teaching Science*. Oxford University Press, 476 pp.

Feller, R.J., and C.R. Lotter. 2009. Teaching strategies that hook classroom learners. *Oceanography* 22(1):234–237. Available online at: https://doi.org/10.5670/oceanog.2009.28.

Fink, L.D. 2003. *Creating Significant Learning Experiences: An Integrated Approach to Designing College Courses*. Jossey-Bass, San Francisco, CA, 320 pp.

# CHAPTER 4. HEAT AND TEMPERATURE

## PURPOSE OF ACTIVITIES

A good grasp of the underlying principles of thermal physics is essential for understanding how the ocean functions and how it impacts climate. Thermal physics is one of the science subjects that students are familiar with and experience on a daily basis, but intertwined with the experiential knowledge they bring to class comes a mixed bag of misconceptions that must be identified and addressed (Carlton, 2000). Example misconceptions include an inability to differentiate between heat and temperature, the notion that transfer of heat will always result in a temperature rise, and a misunderstanding of the concept of latent heat (Thomaz et al., 1995). Another popular misconception concerns confusion regarding the timing of maximum heat flux and maximum temperature—for example, the time of day when Earth's heat flux is largest vs. the time of day when the mean air temperature is highest, or the time of year of maximum heat flux vs. maximum mean water temperature in an ocean or a lake. The purpose of this set of activities is to review basic concepts of thermal physics and to highlight applications to ocean processes. Thermal physics is a vast field, and we do not attempt to cover all aspects of it. Here, we focus on the concepts of heat transfer (conduction, radiation, and convection), latent heat, and thermal expansion. These laboratory activities are completed over two class periods.

## BACKGROUND

***Temperature*** is a quantity that indicates how warm or cold an object is relative to some standard. It is proportional to the average kinetic energy associated with the motion of atoms and molecules in a substance. The Celsius scale (°C) is commonly used to measure temperature. This scale is calibrated to the physical properties of pure water, where the freezing (or triple) point at sea level pressure was arbitrarily set at 0°C and the boiling point was set at 100°C. The familiar Fahrenheit (°F) scale is calibrated so that the boiling point of water is 212°F and its freezing point is 32°F. To convert degrees Celsius to degrees Fahrenheit: multiply by 1.8 and add 32 (°F = 1.8 x °C + 32). The Kelvin scale (denoted as K) is known as the absolute temperature scale, and its zero point is equivalent to -273.16°C (i.e., K = °C + 273.16). Temperature is not measured directly; instead, it is measured indirectly through temperature effects on different materials. Commonly used thermometers measure temperature by means of a change in the volume of a liquid (e.g., bulb thermometers filled with mercury or alcohol) or a change in the electrical resistance of a substance (e.g., ceramic- or polymer-based thermistors).

***Heat*** is defined as internal (kinetic and potential) energy that is being transferred from one substance to another (e.g., Hewitt, 2008). The direction of heat transfer for substances in thermal contact is always from the higher-temperature substance to the lower-temperature substance. This rule does not mean, however, that heat is being transferred from a substance with more internal energy to a substance with less internal energy. Recall that temperature is not directly proportional to the internal energy of a substance; temperature is only a measure of the kinetic (and not the potential) part of the internal energy. Conservation of energy implies that when heat is transferred between systems, the energy lost in one system is gained by the other. Heat has units of energy. In the SI (metric) system, the units are joules. Other units commonly used for heat are BTU (British Thermal Units) and calorie (1 calorie = 4.18 joules). (*Note:* The food-related Calorie [with a capital C] equals 1000 calories, or one kilocalorie.)

Different substances have different thermal capacities for storing heat. The ***heat capacity*** of a substance is defined as the amount of heat needed to raise its temperature by 1°C. The ***specific heat capacity*** ($Q_s$) is the heat capacity per unit mass. Water has one of the highest values of specific heat capacity of any liquid: $Q_s$ = 4186 J/(kg°C) (= 1000 calories/kg°C). The specific heat capacity of air is about one-fourth that of water: $Q_{s_{air}}$ = 1006 J/(kg°C). This difference between the heat capacity of water and air is even more striking considering that specific heat is measured on the basis of mass, and the density of water is about 1000 times greater than the density of air. Thus, *for a given volume,* it takes approximately 4000 times more energy (heat) to raise the temperature of water 1°C as compared to air. Similarly, when water cools, it releases 4000 times more heat than is released when the same volume of air cools (for a video demonstration of the difference between the heat capacities of water and air see https://www.jpl.nasa.gov/videos/oceans-of-climate-change). The specific heat of water is also much higher than the specific heat of rocks and soil.

The higher heat capacity of water allows the ocean to absorb or release large amounts of heat with relatively small changes in temperature compared to the atmosphere or land, both of which have much lower heat capacities. The ocean, therefore, serves as an important heat buffer by keeping Earth's temperature from rising or falling rapidly. This buffering is why coastal locations experience smaller changes in temperature between day and night and between seasons than do nearby inland locations. Land warms up and cools down faster than the ocean under the same conditions of solar radiation.

Latitudinal variations in solar energy flux result in large latitudinal variations in temperature. The ocean plays a key role in moderating Earth's climate, not only by storing/releasing large quantities of heat (due to the high heat capacity of water) but also by transporting heat from higher-temperature equatorial regions to lower-temperature polar regions (e.g., via currents such as the Gulf Stream; Gill, 1982). Without heat transport by ocean currents and winds, differences in temperatures across latitudes would be significantly higher. Mechanisms of heat transport are discussed in more detail below, along with the activities that we use to demonstrate them.

## Mechanisms of Heat Transfer

When a temperature difference exists between two substances, heat is transferred from one to the other by means of *radiation*, *conduction*, or *convection*. Typically, several mechanisms of heat transfer take place simultaneously.

***Radiation*** refers to heat transfer by the emission of electromagnetic waves that carry energy away from the emitting body and are absorbed by another body. All objects absorb and emit energy. The rate of heat absorption depends on the properties of the material and the geometry of the surface interacting with the incoming radiation (see Activity 4.1). If an object's rate of absorption of incoming energy is greater than its rate of energy emission, its temperature will rise (assuming no heat transfer mechanism other than radiation). If the rate of absorption of energy is less than the rate of emission, the temperature of the object will fall. An object will reach an equilibrium temperature when the rate of energy absorption equals the rate of energy radiation.

The quantity and quality (wavelength) of radiated energy depends solely on the temperature of the object. A conceptual model used to describe the relationship between an object's body temperature and its emitted radiant energy is that of a "blackbody." A blackbody refers to an object that completely (100%) absorbs all electromagnetic radiation that arrives at its surface. No electromagnetic radiation is reflected or passes through; therefore, the object appears black. The energy, $E$, radiated by a blackbody per unit of area per unit of time is proportional to the fourth power of its temperature, $T$ (in Kelvin): $E = \sigma T^4$ where $\sigma = 5.7 \times 10^{-8}\ \mathrm{W/m^2\,K^4}$ (Stefan-Boltzmann's Law). This relation implies that if the temperature of a body doubles, the amount of heat it radiates will increase sixteenfold.

Radiation does not occur at one wavelength, but across a spectrum of wavelengths. The peak of the spectrum (i.e., the frequency or wavelength for which the radiation intensity is highest) is inversely related to the temperature (Wien's Law). Thus, as the temperature of a body increases, the peak wavelength of radiation shifts toward shorter wavelengths. For example, the transfer of energy from the sun to Earth's surface is accomplished primarily by radiation. The surface temperature of the sun is 6000 K, and its radiation peak is in the visible wavelength range (relatively short wavelengths). Earth's surface and atmosphere also emit radiation, but their temperatures are lower than that of the sun (~ 300 K), and the radiation peak is in significantly longer wavelengths (infrared). This concept is central for understanding the greenhouse effect. The atmosphere is transparent to the incoming or reflected shortwave solar radiation but not to the longwave (infrared) radiation emitted from Earth's surface or the atmosphere. Thus, energy from the sun reaches Earth's surface, where it is absorbed by land and ocean. The radiated longwave energy, however, is absorbed by atmospheric gases and thus gets trapped in the atmosphere, which acts as a "blanket."[1]

***Conduction*** refers to the transfer of heat between two bodies of different temperatures in physical contact with each other. Heat is transferred by vibration and collision of molecules.

[1] Two misconceptions should be clarified in the context of the greenhouse effect. (1) The term greenhouse is actually misleading. A greenhouse remains warm primarily because convection is inhibited and not because of emission and absorption of longwave radiation by the air in the greenhouse (another analogy that can be used here is how hot it can get inside a car parked on a sunny day with windows closed vs. a car parked with its windows open). (2) The greenhouse effect is not an inherently harmful phenomenon; without it, Earth would be a frigid place. Anthropogenic effects, however, significantly increase the natural insulating properties of Earth's atmosphere, causing Earth's surface temperature to rise further.

Faster-vibrating molecules of a warmer object will collide with slower-vibrating molecules of a colder object, resulting in a net transfer of energy from the faster-vibrating molecules to the slower ones. The rate of heat transfer by conduction is proportional to the area through which heat is flowing (with larger areas allowing for higher transfer rates) and to the temperature gradient (with steeper gradients causing higher transfer rates). The rate also depends on the thermal conductivity of the materials (that is, their ability to conduct heat).

***Convection and advection*** are the major modes of heat transfer in the ocean and atmosphere. Convection occurs only in fluids and involves vertical motion of fluid, or flow, rather than interactions at the molecular level. It results from differences in densities—hence buoyancy—of fluids. Examples of convective processes include: currents in Earth's mantle, which drive the tectonic system and result from heating and cooling of magma; atmospheric circulation resulting from uneven solar heating (e.g., between the poles and the equator); the global ocean conveyor belt and formation of deep water masses, resulting from cooling of surface water at high latitudes; and vertical mixing in the ocean's upper layer due to variations in heating between day and night (for more details see Garrison, 2007, or any other general oceanography textbook). Advection usually refers to horizontal transfer of heat with the flow of water (e.g., the Gulf Stream).

### Latent Heat

When an object gains heat, two things can happen: the temperature of the object can rise, or the object can change its state without a measurable change in temperature (e.g., ice melting into water). Most materials have two state transitions: from solid to liquid and from liquid to gas. The heat needed to change the state of a material is called ***latent heat of fusion*** (for changing from solid to liquid) and ***latent heat of vaporization*** (for changing from liquid to gas). Latent heats of fusion and vaporization for water are high (approximately 334 J/g and 2260 J/g, respectively). These high values have many important consequences for Earth's climate, including the following:

(1) In polar regions, as water freezes during winter, latent heat is added to the atmosphere and surrounding liquid water. In summer, as ice melts, heat is removed from the ocean and atmosphere. Because addition or removal of latent heat results only in a phase change of the frozen water, not a change in its temperature, seasonal changes in ocean surface temperature (and hence air temperature) are relatively small in these regions. Think about ice cubes that keep a drink cold. Only after all the ice melts does the drink's temperature begin to rise.

(2) Water evaporating from the ocean carries latent heat into the atmosphere. This latent heat is released when water condenses to form clouds, warming the atmosphere. Evaporation is also the primary reason why large lakes and the ocean are rarely warmer than 28–30°C.

The human body takes advantage of water's high latent heat of vaporization. A small amount of evaporation can cool a body substantially, which is what we experience when we perspire. The water that evaporates from our skin gains the energy needed to evaporate from the skin itself, which reduces our skin temperature. This phenomenon is also why you feel chilly when you get out of the pool on a hot summer day. A common misconception is that you need to heat water to 100°C for it to evaporate, although people are aware of hanging towels or rain puddles that "dry" at lower temperatures. In liquids, molecules move randomly at a variety of speeds. As a result, they bump into each other and, in the process, some molecules gain kinetic energy and some lose kinetic energy. For some molecules, the gained kinetic energy is sufficient to allow them to break free of the liquid and become gas. The molecules left behind are the slow-moving ones. Thus, the average kinetic energy of the molecules in the liquid decreases when the fast ones "escape" and the liquid is cooled. Heating results in higher average kinetic energy of molecules in the liquid, and statistically more molecules gain the needed energy to "escape" the liquid. Evaporation can even take place directly from the solid phase (called sublimation), as we often observe in Maine (and other similar places) during winter when snow "disappears" even though the temperature remains below the snow's melting point.

### Thermal Expansion

Most substances expand when heated and contract when cooled. As the temperature of most substances increases, their molecules vibrate faster and move farther apart, occupying a larger space. When these substances are cooled, their molecules vibrate slower and remain closer to each other. Note that freshwater below 4°C actually expands when cooled, a phenomena known as the anomaly of water. Thermal expansion is the principle by which a liquid thermometer works. In the ocean, thermal expansion is thought to contribute significantly to sea level rise on decadal-to-century-long time scales. However, thermal effects appear to be influenced by decadal climate-related fluctuations, making it difficult to estimate the long-term contribution of thermal expansion to sea level rise (Lombard et al., 2005). Current estimates suggest that thermal expansion is responsible for 25% to 50% of observed sea level rise.

## DESCRIPTION OF ACTIVITIES

We begin the lesson by asking students to define heat and temperature, usually in small groups of three to four members each. We then gather to discuss their definitions and review mechanisms of heat transport (how does heat "flow"?). Then, through hands-on/minds-on, inquiry-based activities, we illustrate the concepts of absorption and emission of heat (Activity 4.1), heat transfer (Activities 4.1–4.3), latent heat (Activities 4.4 and 4.5), the relationship between evaporation and temperature (Activity 4.6), and thermal expansion (Activities 4.7 and 4.8). During the activities and class discussion sessions, we communicate the underlying principles of these concepts and highlight their significance for ocean and climate processes.

## ACTIVITY 4.1. RADIATIVE HEAT TRANSFER AND ABSORPTION OF RADIATION (Figure 4.1)

### Materials

- Two cans of the same size, one black and one shiny (each can lid should have a hole through which a thermometer can be inserted)
- Two thermometers
- Heat lamp (we use a 150 W white bulb)

*Note:* A pre-made radiation kit is available at https://www.wardsci.com/store/.

### Instructions to the Students

1. You have two cans: one is shiny and the other is black. If the same light source shines on both cans, will the temperature inside the cans be the same? Why or why not?
2. Record the initial temperatures of the thermometers inserted in the cans.
3. Make sure that the cans are the same distance from the light source. Turn on the light and observe the thermometers. What do you see? How can you explain your observations? How is heat being transferred in this system?
4. If you keep the light on for a very long time, will the temperature continue to increase as long as the light is on? Why or why not? By what mechanism(s) is heat being transferred in this system?
5. How do you think principles learned from this activity apply to absorption of electromagnetic radiation at Earth's surface and the regulation of Earth's temperature?

This activity could be modified (e.g., to serve as an assessment tool) to include a can with water in it vs. one without or by using a fan to enhance convection. (Be careful that water does not touch the heat lamp.)

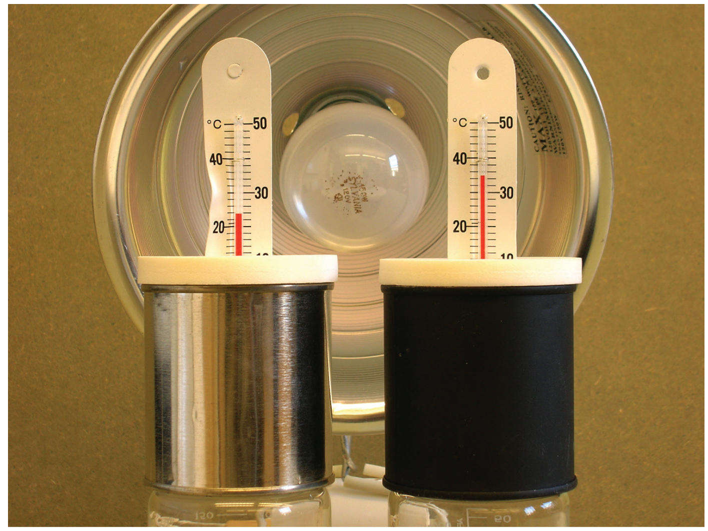


Figure 4.1. Setup for Activity 4.1. The thermometers show the difference in temperature between the black and shiny cans after the cans have been exposed to a light source.

### Explanation

Although the two cans are exposed to the same light source, the two thermometers do not show the same temperature (Figure 4.1). The shiny can reflects more radiant energy than the black can and therefore absorbs less heat. The black can will heat up faster. The temperatures of the cans will not rise indefinitely but will reach a stable final temperature when the gain of shortwave radiation equals the loss of longwave radiation plus the loss of heat to the surrounding air through conduction.

## ACTIVITY 4.2. CONDUCTION (Figure 4.2)

### Materials

- Three types of material at room temperature: wood, metal, and cloth

### Instructions to the Students

1. All three materials have been at room temperature for quite a while. Without touching the objects, predict their temperatures. Will they all feel the same or different with respect to temperature? Why or why not?
2. Briefly place your hand on each material. Does it match your expectations? How would you explain your observations given that all items have been at room temperature?
3. What do your observations reveal about the sensing of temperature by the human nervous system (and that of other organisms)?
4. When and where do you think conduction comes into play in the ocean?

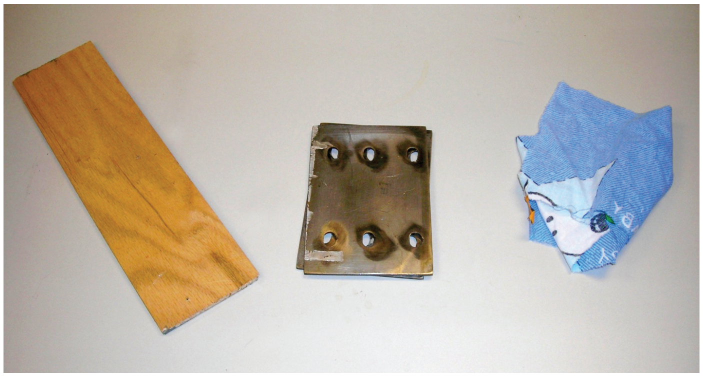

Figure 4.2. Materials for Activity 4.2.

### Explanation

You experience heat transfer by conduction whenever you touch something that is hotter or colder than your skin. Room-temperature materials that are good conductors (e.g., a piece of metal) feel colder to the touch because heat is transferred away quickly, keeping the area we touch from heating up to our body's temperature. Poor conductors (e.g., a piece of cloth) heat locally and thus feel warmer because heat transfer away from our hands is slower. Solids, in general, are better conductors than liquids, and liquids are better conductors than gases. Metals are very good conductors of heat, while air and blubber (fat) are very poor conductors. A tile floor feels colder than a carpeted floor even though both are at room temperature. Tile is a better heat conductor than wool, so heat is transferred away from your bare feet faster on tile than on a rug. Conduction is not a dominant process of heat transfer in the ocean. However, conduction always occurs at the interface between materials of different properties (e.g., liquid and solids, as in the case of marine organisms and the surrounding water; and liquid and gas, as in the case of the ocean and the atmosphere).

## ACTIVITY 4.3. CONVECTION (Figure 4.3)

### Materials

- Convection setup (homemade or use a convection apparatus as in https://www.wardsci.com/store/product/8879574/liquid-convection-apparatus)
- Food coloring (two colors)
- Container with ice-cold water
- Container with hot water

### Instructions to the Students

1. Fill the apparatus with water. (Make sure no bubbles are in the horizontal tubes.)
2. If you warm the right column and cool the left column, what direction would you expect water to flow through the horizontal tubes?
3. Place the right column in the hot-water container and place the left column in the ice-water container. Add a few drops of dye to the two columns (different color to each column) and observe whether the water circulation agrees with your prediction.
4. What if you warm (or cool) only one column of the apparatus? Try it.
5. What ocean and atmosphere processes can be demonstrated using this activity?

### Explanation

When one column of the apparatus is warmed and the other is cooled, density differences are created between the bottom of the vertical tubes, causing a pressure gradient to develop. Density differences cause water masses to sink or rise until they reach their density equilibrium level; once a water mass reaches its equilibrium density level, it begins to move horizontally in response to a pressure gradient. (*Note*: Pressure gradients result from differences in the vertical distributions of density, and hence hydrostatic pressure, between regions where water is denser or lighter.) Because the cold water is denser, it will move along the lower connecting tube; the hot water will move along the upper connecting tube (Figure 4.3). If you cool or warm only one column, you will see the same effect though it may not appear as dramatic because the pressure gradients will be

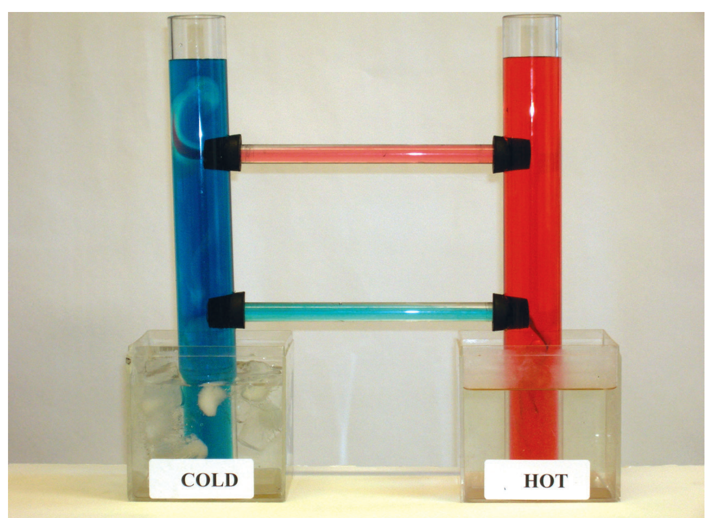


Figure 4.3. Convection apparatus. Note the warm water (red) flows at the top and the cold water (blue) at the bottom due to the difference in density between the fluids on opposite sides.

smaller. This activity provides a good illustration of density-driven ocean circulation—for example, the global conveyor belt. It is important, as with any demonstration, to draw students' attention to where an analogy breaks down so misconceptions do not arise. For example, the global conveyor belt results from cooling at the water surface, while in this demonstration cooling and heating are done from the bottom (the atmosphere, on the other hand, is heated from below so atmospheric buoyancy-driven circulation is a better analogy). This activity can be also used in conjunction with Chapter 1.

## ACTIVITY 4.4. HEAT PACK (Figure 4.4)

### Materials

- Two containers with water
- Reusable heat pack (from Arbor Scientific) at room temperature
- Two thermometers
- Watch or stopwatch

*Note*: We usually do this activity as a class demonstration. If you intend to use this activity with multiple groups, you will need to obtain several heat packs (which are inexpensive). Once a pack is activated and the material in it solidifies, you will need to heat it for about 20 minutes to return it to the liquid phase.

### Instructions to the Students

1. Observe, feel, and describe the heat pack (e.g., material and temperature).
2. Fill the containers with room-temperature water and record the initial temperature of each.
3. Activate the heat pack by pressing the button (use the ball of your fingers—don't use your nails, as they might damage the pack) and add it to one of the containers. The other container serves as a control.
4. Immediately record the starting temperature in both containers.
5. Continue recording the temperature in each container, once every minute for 10 minutes.
6. Did you observe differences in the water temperature between the two treatments? What causes the change in water temperature? How does this pack work? (*Hint*: Did the material in the pack look the same before and after you activated the pack?)
7. What processes in the ocean and atmosphere are analogous to what you just observed in this activity (a phase change followed by a change of temperature in the surrounding waters)?

Figure 4.4. Materials for Activity 4.4.

### Explanation

When an activated heat pack is placed in water, the water temperature begins to rise. In contrast, water temperature in the control container (without the heat pack) remains constant. The heat pack contains a supersaturated aqueous solution of sodium acetate. When the pack is activated, a nucleation center is formed and the sodium acetate begins to crystallize, releasing stored energy as heat. The released heat is being conducted from the pack to the water, and fluid motions (convection and advection) distribute the heat within the water in the container. To return the pack's contents to the liquid phase, you will need to heat the pack (i.e., "invest" energy). This activity demonstrates the heat release that accompanies a phase change and can be discussed in class in the context of latent heat released during ice formation and cloud condensation.

## ACTIVITY 4.5. HEAT FLOW AND LATENT HEAT (Figure 4.5)

### Materials

- A small plastic container with a top. The container should be small enough to fit inside a Styrofoam cup. Drill a hole in the top of the container, large enough to fit a thermometer.
- Styrofoam cup(s). Nest several cups within each other for better insulation. Mark the cup with a line to indicate the volume of water that needs to be added so that the volume of water in the plastic container is the same as the volume of water in the Styrofoam cup.
- Two digital thermometers
- Ring stand with a clamp and platform
- Hot tap water, ice-cold water, and ice

### Instructions to the Students

1. Draw a cartoon of the experimental setup (Figure 4.5) and using arrows indicate the direction of heat transfer if the small plastic container contained ice-cold water (with no ice) and the Styrofoam cup contained hot water. What would happen to the temperature of the water in the small plastic container? What would happen to the temperature of the water in the Styrofoam cup?
2. Fill the small plastic container to the top with ice-cold water (no ice!). Record the initial temperature of the water in the container. Affix this container to the clamp.
3. Fill the Styrofoam cup with hot tap water to the marked line (so the volume of water in the container equals the volume of water in the cup). Record the initial temperature of the water in the cup.
4. Slide the arm of the clamp down and place the small container inside the cup so that it is immersed in the hot water. Record the temperature in the container and the cup every 30 seconds for four minutes. Using the rod of the thermometer, mix the water in the cup and the container while doing the measurements to eliminate any temperature gradients that might be developing. (In other words, don't allow light, warm water to accumulate and float on top of cold, denser water.)
5. Plot the temperature in the container and the cup as a function of time. Do your observations agree with your prediction? What do you expect the temperature gradient to be after a longer period of time?

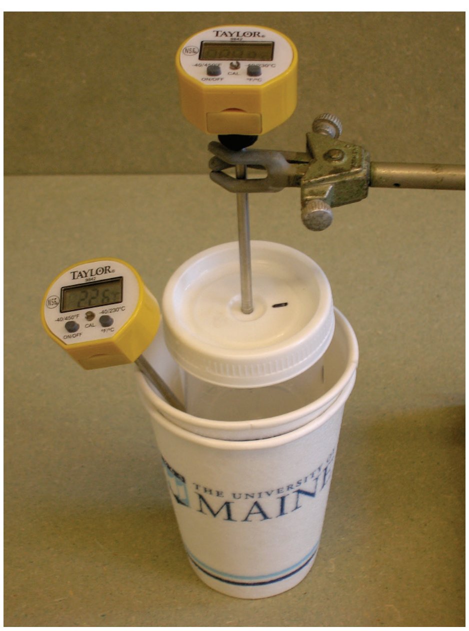

Figure 4.5. Setup for Activity 4.5.

6. Assume that you repeat the experiment, but this time you fill the small plastic container with ice + water and fill the cup with hot tap water (don't do it yet!). Do you expect to see similar changes in temperature in this setup? Why or why not?
7. Fill the small container to the top with ice and water (approximately 60% ice and 40% water). Record the initial temperature of the water in the container.
8. Repeat Steps 4 and 5. Do you see the same trend as you saw in Step 5? Why or why not?

### Explanation

Heat is transferred through conduction from a high-temperature substance to a lower-temperature one. In this experiment, heat is transferred from the hot water in the Styrofoam cup to the cold water in the plastic container in the middle of the cup. As a result, the temperature of the water in the cup decreases (heat is removed) while the temperature in the inner plastic container increases (heat is gained). After a long period of time, the system will reach equilibrium, and there will be no temperature gradient between the water in the Styrofoam cup and the water in the container. When ice + water is added to the plastic container and hot water is added to the cup, heat transfer is in the same direction as before—but now, while the temperature of the hot water decreases, there is no observed change in the temperature of the water + ice (because heat is invested in melting the ice). Only after all the ice melts will the temperature of the water in the plastic container begin to rise.

## ACTIVITY 4.6. SLING PSYCHROMETER (HYGROMETER) (Figure 4.6)

### Materials

- Sling psychrometer (can be purchased from https://www.wardsci.com/store/product/8874236/sling-psychrometers-celsius-fahrenheit-sper-scientific)

### Instructions to the Students

1. A sling psychrometer is a device that allows us to measure relative humidity by comparing the temperature of a thermometer wrapped in a wet cloth (the wet bulb) with the temperature of a dry bulb. How do you expect the temperature between the two thermometers to vary as a function of humidity? Why might there be a difference between the two readings?
2. Swing the psychrometer for 20 seconds and then note if there is any difference in temperature between the two thermometers. (We ask students to take at least three readings and find the median. We use these data later for a discussion on measurements).

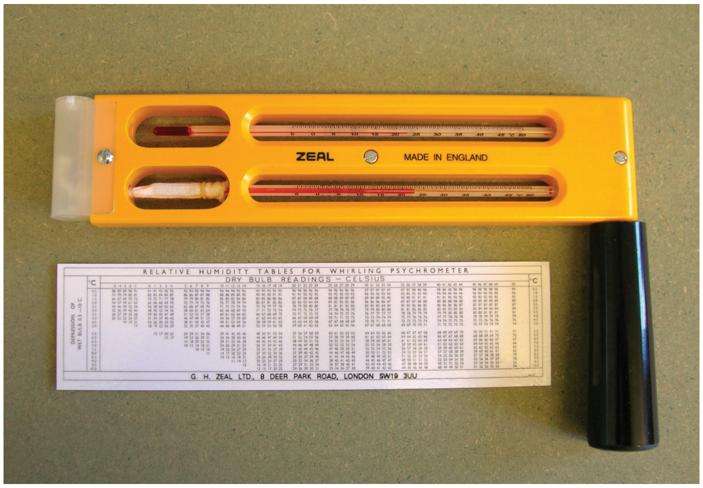


Figure 4.6. A sling psychrometer and its conversion table.

After the activity, have the students discuss the concept of humidity and describe the expected relationships among humidity (mugginess), evaporation, and ambient temperature. Following this discussion, students should be able to explain (possibly as an assessment) how one could use the psychrometer to determine humidity at a given ambient temperature (as is done with a table provided by the manufacturer; Figure 4.6).

### Explanation

The sling psychrometer consists of two thermometers mounted together. One is a regular thermometer; the other is a wet-bulb thermometer (which has a wet cloth "sock" over the bulb). When you whirl the instrument, water evaporates from the wet cloth (in contact with fresh air), cooling the wet-bulb thermometer. The temperature of the wet bulb reaches equilibrium when cooling due to evaporation of the fluid (which depends on the relative humidity in the room) is in equilibrium with the gain of heat through conduction from the surrounding air. If the surrounding air is dry, evaporation will be high, and the difference in temperatures between the two thermometers will be greater. If the air is saturated with water vapor, no evaporative cooling will take place, and there will be no difference in temperature between the two thermometers.

## ACTIVITY 4.7. THERMAL EXPANSION (Figure 4.7)

### Materials

- Flask
- One-hole stopper
- Long glass tube
- Container filled with hot water
- Food coloring
- Lab tape

### Instructions to the Students

1. Fill the bottle with colored water. Push the stopper down until the fluid rises one-third the length of the tube above the stopper. Mark the water level with tape.
2. What do you expect will happen to the water level in the tube when you place the flask in a container with hot water? Why?
3. Place the flask in a container filled with hot water. Observe the water level in the glass tube for at least three minutes. Mark the new water level. Does it agree with your prediction?
4. Apply what you have learned in this activity to predict and explain what will happen to the ocean's volume if ocean waters become warmer. What would be the implications for sea level?
5. What other processes influence sea level? *Challenge*: Would the melting of land-based ice and sea ice have the same effects on sea level? Why or why not? How would you test your prediction?

### Explanation

When a fluid is heated, it usually expands; when cooled, it usually contracts (with some important exceptions, e.g., $H_2O$ below 4°C). This is the principle by which a mercury or ethanol thermometer operates. Increased heating of the ocean due to global warming will result in seawater expansion, and the increase of water volume in ocean basins will cause sea level to rise. Other processes contributing to sea level change include the addition of water from the melting of glaciers and land ice caps, and the rise and fall of lithospheric plates due to isostatic leveling.


Figure 4.7. Setup of Activity 4.7 following the flask's immersion in hot water.

Melting of sea ice does not change sea level because the volume of water displaced by an iceberg equals the volume added when it melts. To demonstrate this concept, ask the students to place a large block of ice in an aquarium and record the water level before and after the ice melts. *Note*: Some "sea level" change may be observed if the ice cools the water enough to cause significant contraction.

## ACTIVITY 4.8. REVERSING RODS (Figure 4.8)

### Materials

- Two glass beakers: one filled with cooled water (below 20°C) and one filled with warm water (~ 40°C)
- A set of reverse density rods: one aluminum rod, one plastic rod (from Arbor Scientific)
- Thermometer
- Ice (may be needed to cool water)
- Hot plate (optional; hot tap water will work fine)

### Instructions to the Students

1. What will happen to the rods (float/sink) if you place them in a beaker with cold water? What is the reasoning behind your prediction?
2. Place the rods in the beaker with cold water. Make sure no air bubbles are attached to the rods.
3. Does your observation agree with your predictions? Observe the rods for at least five minutes.
4. Repeat this experiment, this time using the beaker filled with hot water. Observe the rods for at least three minutes. What is happening?
5. How would you explain the different behaviors of the rods in cold vs. warm water? With your group, discuss possible explanations for what you have observed.

### Explanation

In this activity, one rod is made of aluminum and the other of PVC. When you place the rods in cold water, both initially float because their densities are lower than that of the cold water. Over time, the PVC rod gets colder and contracts, which results in a density change. (Its volume decreases, but its mass remains the same.) When the density of the rod exceeds that of the water, the PVC sinks. The aluminum rod gets colder too, but aluminum expands and contracts much less than PVC when its temperature is changed by the same amount (that is, it has a smaller "thermal expansion coefficient"). Therefore, the aluminum rod's density is less affected by the temperature change, and the aluminum rod remains floating. When you place the rods in

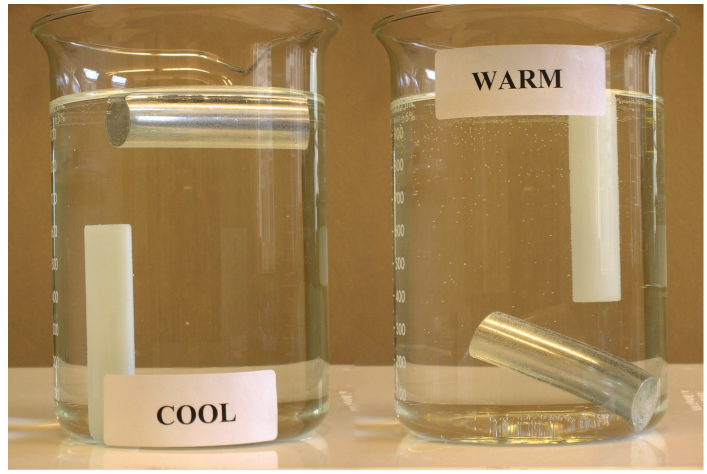

Figure 4.8. Aluminum and plastic rods immersed in cold and warm water.

hot water, the density of the water is now lower than that of the aluminum rod, and the rod sinks. The PVC rod is also initially denser than the water and it sinks too, but it expands significantly as it warms. As a result, its density decreases (again, its mass remains constant, but its volume increases). When its density becomes lower than that of the water, it floats. This activity can be also used in Chapter 1.

## SUPPLEMENTARY ACTIVITY

We have noticed that many students confuse the time of the day at which solar radiation is maximal (around noon) with the time of the day at which the temperature is maximal (several hours later in the afternoon). Similarly, students confuse the shortest or longest day of the year, when incoming solar flux is close to minimal or maximal values, with the time of year when air temperature or water temperature in the ocean and in lakes are (on average) the coldest or warmest (ignoring nonradiative processes that affect water temperature, such as upwelling). This issue stems from confusion about temperature versus the rate of change of temperature. *The rate of change of temperature is proportional to the heat flux (when no phase transition takes place).* As a class activity, we ask students to draw a qualitative cartoon of what they think a plot of water temperature vs. time of year would look like. We then ask them to go to the NeraCOOS Website (https://www.neracoos.org/data/index.html or any other website that provides real-time sea surface temperature) to plot the annual sea surface temperature (weekly or daily averages) vs. time, and to observe when the water or air temperature is maximal. (This activity can be done as a homework assignment.) In class, we discuss the difference between temperature and the rate of change of temperature that is associated with the heat flux. For example, the radiative heat flux in Maine (hence, the rate of change of temperature) is, on average, lowest in December and highest in June (associated with the shortest and longest days of the year). The ocean and atmosphere, however, continue to lose heat after December (or gain heat after June), even though the radiative heat flux is not at its minimal (or maximal) value. Thus, the water temperature continues to drop after December and continues to rise after June. The temperature will stop changing (reaching a maximum or minimum value) when the heat gain equals the heat loss. In the Gulf of Maine, maximum average sea surface temperature occurs in September, not June. A similar argument can be presented to explain why the hottest period during a day is not noon, when the flux of incoming solar radiation is close to its maximal value, but a few hours later. An analogy some students are familiar with is the time lag between the maximal acceleration of a car when they floor the gas pedal and when the car speed is maximal (which occurs later, when acceleration processes and deceleration processes are equal). Acceleration (time rate of change of velocity) is the analogue for heat flux (proportional to the time rate of change of temperature, assuming no phase transitions).

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## OTHER RESOURCES


Sorbjan, Z. 1996. *Hands-On Meteorology: Stories, Theories, and Simple Experiments*. American Meteorological Society, Washington, DC. A collection of hands-on experiments designed around concepts of meteorology. Chapter 4 addresses heat. In addition to the experiments, the book contains historical narratives, references to important discoveries, and stories about famous and infamous scientists.

# TEAM-BASED LEARNING

*Team-based learning*, also referred to as *cooperative learning*, is a pedagogical approach in which students work in small groups to achieve learning goals. It provides students with opportunities to converse with peers, brainstorm, present and defend ideas, and question conceptual frameworks. In this approach, the instructor acts as a facilitator and content expert rather than a lecturer. Team-based learning can develop problem-solving, communication, and critical-thinking skills. In addition, it can increase students' self-esteem and their ability to work with others, as well as improve their attitudes toward learning (Slavin, 1981). Much has been written about this strategy, including a book we recommend on cooperative learning, written by an oceanographer (McManus, 2005). The University of British Columbia website on team-based learning contains a wealth of information (https://cis.apsc.ubc.ca/teaching-strategies/team-based-learning/). Our goal here is to highlight key elements of cooperative learning, as this strategy integrates well with the inquiry-based teaching and learning approach we advocate.

Team-based learning can be used in the classroom or lab or outside the classroom to help students complete class assignments. It can take many different forms (e.g., Hassard, 2005; Joyce and Weil, 2009). Examples include:

- *Think-pair-share*. Students are asked to first think about a question or a problem independently and then discuss their ideas with the student sitting next to them. Each pair then shares their ideas with the class.
- *Roundtable or circle of knowledge*. A group of three or more students brainstorm on an assigned problem and record their ideas. Each group then presents its ideas to the class.
- *Jigsaw*. In teams, each student is assigned to research one aspect of the learning assignment. Students then teach their topic to their team members. Students assigned the same topics can form "expert groups" to brainstorm and discuss their topic before presenting it to their own teams.
- *Constructive controversy*. Teams or pairs of students are assigned opposing sides of an issue. Each team researches, prepares, and presents its argument. The class discusses the issue after all teams have presented.

## ESSENTIAL ELEMENTS

Regardless of the specific strategy used for team-based learning, several essential elements are required for this approach to be successful. First, the instructor must promote individual and group accountability for learning, making sure that group time is, indeed, used for achieving group learning goals and not for social conversation. Second, the instructor must achieve interdependence among the students in the learning teams, and the students must know that a "chauffeur/hitchhiker" situation is unacceptable. Teammates must know that the team's success depends on individual learning by each team member and must feel that they need each other in order to complete the group's task (i.e., they "sink or swim" together). These first two elements can be achieved by dividing tasks, assigning roles, providing feedback, and assessing individual learning outcomes. To avoid a "chauffeur/hitchhiker" situation, team members can be randomly assigned to take leading roles and to represent their groups during class discussions.

Another important element is that students must learn and develop cooperative skills. Skills include those for working together effectively (e.g., active listening, staying on task, summarizing, recording ideas) as well as maintaining group "spirit" skills (e.g., encouraging each other, providing feedback). Finally, students should be given the opportunity to reflect on how well they work as a team. The determination of how well groups are functioning and how well they are using collaborative skills can be assessed on an individual, team-wide, or whole-class basis.

Our experience is that students who have not previously been involved in cooperative learning do not initially like this approach because they are concerned that their grades will be affected by other team members. We tell students, therefore, that peer evaluation of the group's project and functionality will contribute a certain fraction to the final grade. The team's peer evaluation is done by each team member individually, and students are assured that their evaluations will not be shared with other team members. Students are prompted to evaluate how well the team collaborated, using questions (e.g., Angelo and Cross, 1993) such as:

- How well did your group work together on this assignment?
- How many of the group members participated actively most of the time?
- How many of the group members were fully prepared for the group work most of the time?
- Give one specific example of something you learned from the group that you probably wouldn't have learned working alone.
- Give one specific example of something the other group members learned from you that they probably wouldn't have learned otherwise.

Each student is also asked to provide a self-evaluation, through questions such as:

- How comfortable did you feel working with the group?
- Were you an active participant?
- How well did you listen to team members?
- To what degree did you help other team members to better understand the material?
- Did you ask for help from a team member when you did not understand an idea or concept?

Finally, each student is asked to evaluate the percent contribution (out of 100%) of each team member, except self, to the assignment and provide an explanation for the evaluation. Information on grading formulas for peer evaluations can be found on the Team Based Learning website: https://cis.apsc.ubc.ca/teaching-strategies/team-based-learning/.

Teams can be formed by the students (self-selection) or by the instructor (randomly or purposefully). Self-selected and randomly assigned teams can result in groups that are not heterogeneous and/or not equal in ability. As a rule, groups should stay together long enough to feel successful as a group, but not so long that team dynamics become counterproductive (e.g., when team members settle into fixed roles). Group size may also vary. In smaller groups, each member generally participates more, fewer social skills are needed, and groups can work more quickly. In larger groups, more ideas are generated and a smaller number of group reports is produced.

It is not enough to simply tell students to work together. Incentives and a healthy sense of competition can enhance students' motivation, engagement, and contributions to the team. Reward structures may be based on team points (the team with the most points wins), on criterion achievement (any team reaching a predetermined criterion, such as all team members scoring 85% or better, receives a reward), or on team improvement (students contribute to their teams by improving over their past performances). In the team-improvement case, high, average, and low achievers are equally challenged to do their best, and the contributions of all team members are valued.

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# CHAPTER 5. GRAVITY WAVES

## PURPOSE OF ACTIVITIES

The purpose of these activities are to familiarize students with wave motion in general and gravity waves in particular. Concepts such as resonance, natural frequency, and seiche are demonstrated. Other topics that are emphasized during class discussion are measurements and their statistics, and dimensional analysis.

## BACKGROUND

Waves are ubiquitous in the ocean and in lakes; surface gravity waves, in particular, are a common sight at beaches. Gravity waves are important in a variety of oceanic processes, including the passage of momentum from wind to the ocean, mixing enhancement through wave breaking, beach erosion, and accumulation of floating debris at beaches. Their importance in recreation and popular culture (surfing) and their destructive powers (tsunamis) make them familiar even to students living inland. However, such waves are seldom used to teach about harmonic motions at the college and high school levels.

## DESCRIPTION OF ACTIVITIES

We start the lesson by asking the students to describe waves they are familiar with and that are associated with the ocean. Most are familiar with surface gravity waves, tsunamis, sound, and light. We use a Slinky to demonstrate differences between transverse and longitudinal waves (e.g., Hewitt, 2008). We discuss wave descriptors such as wavelength, frequency, amplitude, period, propagation (or phase) speed, and the direction of movement of particles in the medium. We discuss what is carried by waves (energy, information) versus what is not (components of the medium; e.g., a piece of foam bobs up and down as waves pass but doesn't propagate significantly with them over a wave period). As an analogy, we give the example of a stadium-audience wave that is achieved when spectators stand and raise their hands in sequence. The wave travels through the crowd, and it is easy to see how information is transferred while the spectators remain in place in their seats. Time could be saved by providing reading materials prior to class (e.g., Chapter 13 of Denny, 1993), familiarizing students with waves and allowing for in-class exploration of additional topics such as capillary waves and internal waves. The following activities are presented as a sequence that the class follows collectively, with students seated in small groups of three to four members to facilitate discussion.

## ACTIVITY 5.1. WAVE SPEED AND WATER DEPTH (Figure 5.1)

### Materials

- Rectangular tanks marked at 1.5 cm above the bottom and 6 cm above the bottom (from https://www.wardsci.com/store/)
- Stopwatches
- Container with water

### Procedure and Explanation

We first ask students to suggest what characteristics may affect the speed of a small-amplitude wave (by small we mean that its height << wavelength). Quantities usually suggested are gravity ($g$, gravitational acceleration [the restoring force]; dimension $L/T^2$), wavelength ($\lambda$; dimension $L$), depth ($H$; dimension $L$), and density ($\rho$; dimension $ML^3$). From dimensional analysis alone (Box 5.1), we come up with the wave propagation speed being proportional to $\sqrt{gH}$ or $\sqrt{g\lambda}$ times any function of $H/\lambda$. Generally speaking, waves with a wavelength smaller than the depth over which they travel (i.e., deep water waves, $\lambda << H$) do not interact with the bottom, and their velocity is dependent on the wavelength (termed "dispersive" waves). Waves with a wavelength larger than the depth over which they travel (i.e., shallow water waves, $\lambda >> H$) do interact with the bottom, and we expect the depth to be a factor in their propagation (these are "non-dispersive" waves). Longer-wavelength waves penetrate deeper (the depth of wave penetration and the decrease of its amplitude

Figure 5.1. Wave speed and wave depth. Students measure the number of "sloshes" in a tank filled with water to a depth of 1.5 cm.

## BOX 5.1. DIMENSIONAL ANALYSIS

Dimensional analysis is a powerful technique used to explore likely relationships between an observed phenomenon and the physical variables associated with it. Most physical quantities can be expressed in terms of some combination of five dimensions: length ($L$), mass ($M$), time ($T$), electrical current ($I$), and temperature ($t$).

For example, let's say that we would like to know what physical attributes determine the period of a swing. The physical characteristics of the swing are its mass ($m$, $[M]$) and the length of the rope ($l$, $[L]$). The restoring force acting on it is gravity (associated with the gravitational acceleration $g$ $[L/T^2]$). How can we use all of these variables to obtain the dimension of time associated with the period of the swing? The only combination that provides this dimension is $\sqrt{l/g}$. Surprisingly (to some), this simple analysis suggests that the mass of the swing plays no role. These results can easily be verified empirically.

Dimensional analyses have been very useful in fluid dynamics in general and in geophysical fluid dynamics in particular, given the complexity and nonlinearity of the ruling mathematical descriptions. Use of dimensions and scaling helps to simplify equations (by "scaling out" terms) to study a given phenomenon.

from surface to depth both scale with its wavelength). The wave is at the interface, but motion associated with the wave is felt at depth. To test whether wave velocity is dependent on the fluid's depth, we do the following activity.

Each group of students receives a small rectangular tank ($L$ = 30-cm long). The tanks are filled with water 1.5-cm deep. Students are asked to create a wave by lifting one side of the tank off the table, then setting it back down, and to record the number of times the disturbance bounces back and forth from the walls in a time interval of 5 s (there are ~ 6 sloshes during this period; Figure 5.1). Students are then asked to figure out how to turn this information into a measure of velocity (length of tank times sloshes per unit time = 30 cm x 6/5 s ≈ 0.36 m/s vs. the velocity calculated from dimensional analysis: $\sqrt{gH}$ = 0.38 m/s). Expected uncertainties are on the order of 10–20% (given reaction time and accuracy of locating the position of perturbation at the end). The tanks are then filled to a depth of 6 cm. Repeating the measurements of wave propagation indeed shows that the wave bounces about 12 times in 5 s (velocity ≈ 0.72 m/s vs. the velocity calculated from dimensional analysis: $\sqrt{gH}$ = 0.76 m/s). Note that no dependence on the initial wave amplitude (variable between groups) is observed. The wave in the tank has a wavelength of 60 cm ($\lambda >> H$). We discuss the fact that if the theoretical prediction is correct (dependence on $\sqrt{H}$), quadrupling the depth should double the wave velocity and hence the distance traveled in 5 s (as is observed). If multiple groups participate or if replications are done, statistical descriptors of the results, such as mean and median speeds and measures of variance and their uncertainties, can be introduced and computed.

At this stage, we ask the students whether a tsunami is a deep or shallow water wave. Because a tsunami's lateral extent is determined by the length of the fault zone ruptured during the earthquake (~ 100,000 m) and the maximal depth of the ocean is significantly smaller (~ 11,000 m), it qualifies as a shallow water wave. Then, why is it so destructive? Given that speed is depth-dependent (~ $\sqrt{H}$), surface gravity waves slow down as bathymetry shoals and wavelength shortens. That is, the "front" of the shallow water wave propagates slower than its "back" when depth decreases. Wave shoaling increases the wave's steepness (as trough and crest get closer), causing the wave to eventually break. In the open ocean, a tsunami might have a speed of several hundred kilometers per hour and a height of only a few centimeters, but as the wave approaches shore, its speed slows and its height increases significantly, sometimes up to many meters.

The slowing of waves in shallow water also causes wave refraction when waves arrive at a beach at an angle. Wave refraction, well known to some from Snell's Law, refers to the change of wave front directions due to a change in propagation speed. As a wave approaches the shore at an angle and "feels" the seafloor, the "wave train" in shallow depth slows compared to the part at deeper depth, causing it to align more closely with bathymetric contours. Many good images of wave refraction can be found on the Web by using Google Image Search.

## ACTIVITY 5.2. INTERNAL WAVES (Figure 5.2)

### Materials

- Rectangular tanks with a divider (from https://www.wardsci.com/store/)
- Stopwatches
- Two containers: one with freshwater and the other with dyed salty (or sugary) water (approximately 75 g kosher salt dissolved in 1 L tap water)

### Procedure and Explanation

The same rectangular tanks are used to demonstrate and discuss internal waves that form at the interface of fluids of different densities (e.g., stratified layers in the ocean; see Activity 1.4). The tanks can be separated into two compartments by inserting a plastic divider. Students are asked to fill one compartment with freshwater and the other with salty (or sugary) dyed water, and they are asked to predict what will happen when the barrier is removed (see also Activity 1.4). The barrier is then removed, and the denser fluid flows under the less-dense fluid. Once the fluid from each compartment reaches the opposite end of the tank, an internal wave propagates back and forth along the interface between the two differently colored fluids (Figure 5.2). Students are asked to measure the wave's speed, which is significantly slower than both surface gravity waves they encountered earlier. In the ocean, breaking internal waves are responsible for mixing of heat and nutrients at the base of the mixed layer and in the vicinity of steep topography (e.g., Kunze and Llewellyn Smith, 2003). Internal waves can also uplift waters from darkness to a sunlit position closer to the surface where phytoplankton populations may get sufficient light for growth. For the same excitation energy and wavelength, the amplitude of internal gravity waves is significantly larger than that of surface gravity waves, because the gravitational restoring force (and potential energy associated with these waves) for a given wave height is smaller for internal waves, given the small density contrast between the layers of water as compared to that of water and air for surface gravity waves. (For an alternative illustration of internal waves, see Franks and Franks, 2009.)

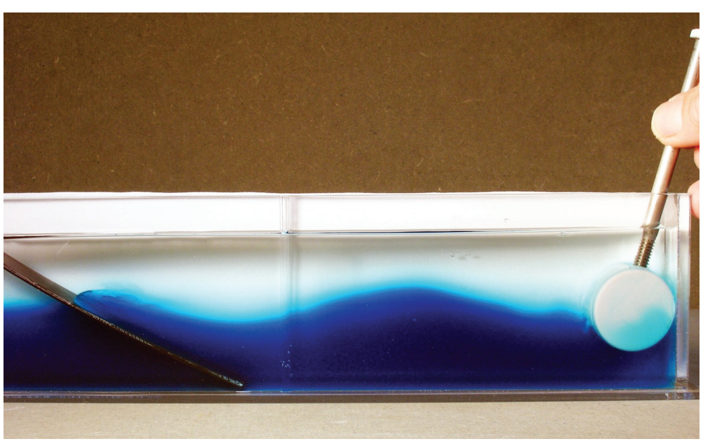

Figure 5.2. Internal waves. An internal wave at the interface between two fluids of different densities (dense blue water and less-dense clear water). A wave paddle that can be used to demonstrate resonance (see text) is shown on the right side of the tank, and a piece of plastic that simulates shallowing topography is shown on the left side of the tank.

At this stage, we introduce the concepts of *seiche* and *resonance*. When we perturbed the two-layer system by lifting the tank divider, many waves were initially excited. But only those that fit (resonate) with the geometry of the basin remain. We end up with a single wave that propagates back and forth in the tank with a specific rhythm. Similar to a musical instrument where a different primary tone is produced for a given size of string or air chamber, the geometry of a water basin (e.g., the experimental tank, a lake, or a bay) determines which waves are excited when forcing is applied and then released (e.g., due to a storm passage). These waves are the "natural" modes of the basin and are termed "seiche"; their frequency is described as the "natural" frequency. Forcing a tank at its natural frequency excites these waves, a phenomenon termed "resonance." To demonstrate resonance, we use a wave paddle (a wide piece of plastic about 2-cm high, with a width similar to that of the tank; Figure 5.2). We lower and raise the paddle in a stratified tank at a period matching the period of the waves excited earlier. That is, when we apply short-period forcing (i.e., lowering and raising the paddle at a frequency of ~ 1 s), surface gravity waves are formed (beware of spilling). When a longer period of forcing is applied (i.e., lowering and raising the paddle at a frequency of ~ 10 s), internal waves are formed. A piece of plastic inserted at an angle at one end of the tank will simulate shallowing topography, allowing the observation of breaking internal waves (Figure 5.2).

## ACTIVITY 5.3. BUOYANCY OSCILLATIONS (Figure 5.3)

### Materials

- A tall graduated cylinder with a stratified fluid (salty water on the bottom and freshwater on top)
- A ping-pong ball with clay attached as ballast (or a test tube filled with washers [weights] for ballast) such that the ball (or test tube) stays put near the interface between the two fluids.

## Procedure and Explanation

Buoyancy oscillations, the highest-frequency internal waves found in the ocean, can be easily demonstrated using a graduated cylinder and a calibrated float (Figure 5.3, left panel) or a weighted ping-pong ball with clay attached as ballast (Figure 5.3, right panel). Dense, salty water is introduced and overlaid with freshwater. The float is introduced at the interface between the two layers and is perturbed by pushing it downward with a thin rod. The oscillation's frequency (called the buoyancy or Brunt-Vaisalla frequency) is a function of the contrast in density between the two layers. The frequency is proportional to the square root of the density gradient, as expected from dimensional analysis. Students can examine this dependence by timing the oscillations in graduated cylinders containing different density gradients. For advanced students, the mathematical description of this problem can be introduced. The mathematics is relatively simple (culminating in a one-dimensional wave equation) and rewarding (e.g., Gill, 1982).

The subject of fluid waves is vast and fascinating (see, for example, the advanced textbooks by LeBlond and Mysak, 1978, and Lighthill, 1978). Fluids support a wide variety of waves, spanning physics topics from surface tension, to sound, light, and gravity waves, to vortical planetary waves (large-scale waves with significant angular momentum, affected by Earth's rotation). Because waves are the information-carriers in a fluid, any change in forcing (e.g., a change in wind patterns over the ocean) results in the excitation of waves. An example is the La Niña/El Niño transition, when the trade winds are significantly weakened over the equatorial Pacific region. This change excites Kelvin waves that propagate from west to east along the equator, as can be observed in remotely sensed images of the height of the ocean's surface (e.g., https://www.aviso.altimetry.fr/en/applications/climate/el-nino.html). Impacts on the ocean's biology can be observed in remotely sensed ocean color data/images as well (e.g., https://svs.gsfc.nasa.gov/stories/elnino/index.html).

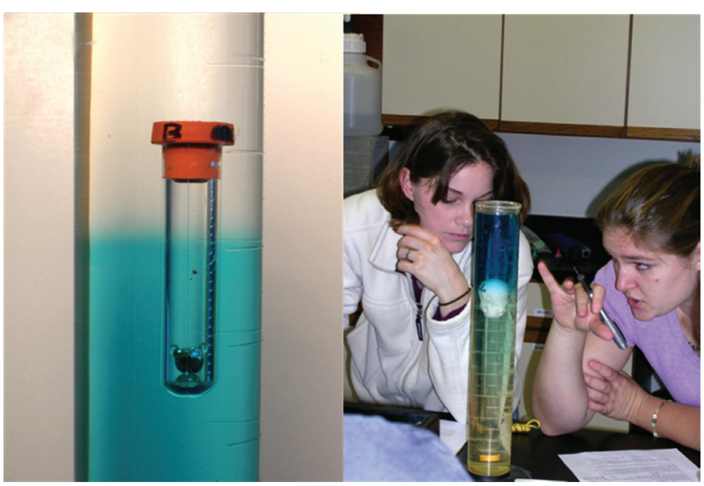

Figure 5.3. Buoyancy oscillations. An object of intermediate density rests between layers of dense bottom fluid and less-dense top fluid. If pushed down, the object will oscillate with a frequency dependent on the difference between fluid densities.

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Movies of shear-induced breaking internal waves (Kelvin-Helmholz instability): https://www.gfd-dennou.org/library/gfd_exp/exp_e/index.htm.

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