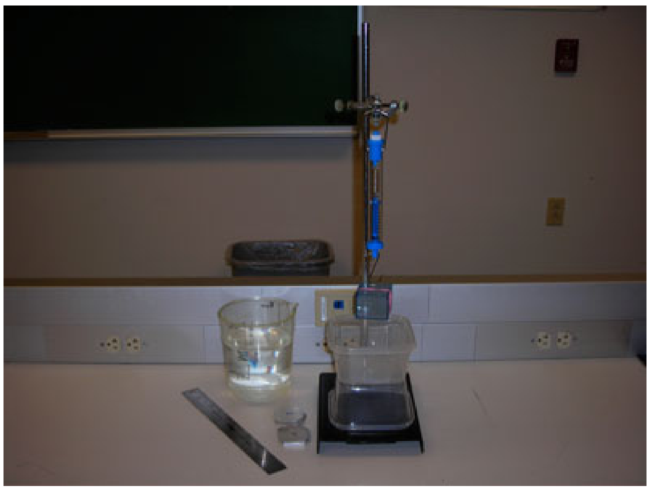
TEACHING SCIENCE BY OCEAN INQUIRY
Buoyancy

Part I

Comments: The activities below explore the factors that govern the sinking and floating behaviors of an object. The instructions for these activities are deliberately written to demonstrate the idea that "hands-on" can be done at different levels of inquiry. A class discussion about the pedagogy and science concepts will follow.

1. Archimedes' Block



Materials: (all obtained from sciencekit.com)

- Archimedes' block (box)
- Spring scale
- 5 g and 10 g masses
- A container with water
- Ring stand
- Ruler
- Balance
- Graph paper (optional)

Instructions:

1. Measure/compute the volume and weight of the box without the weights.

2. Begin adding mass to the box in increments of 25 g (weights are labeled 5 or 10 corresponding to 5 g and 10 g, respectively). After each time that you add mass measure:
    a. The weight of the box outside the water (using the spring).
    b. The weight of the box in the water.
    c. The depth to which the box is immersed in water (each mark on the box is 1 cm).
    d. Record your data in the table below:

Added mass (gr.)	Weight in air	Weight in water	Immersion depth

3. Plot the depth of the box immersed in water as function of the weight of the box + the added weights. Obtain the slope of your plot.
4. What should the slope be based on Archimedes's principle? How does it compare to the slope of your plot?
5. Place 100 g in the box. What is the weight of the box in water? What is the difference between the weight of the box in water and in air? Is this difference reasonable given what you know about buoyancy?

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2. Archimedes' Ball

Materials:

- Archimedes' ball (sciencekit.com)
- Syringe
- A piece of tubing

- Scale
- Caliper
- A container with water
- A container with an unknown solution

Instructions:

1. Imagine the plastic ball is a submarine. You want it to remain under water such that only the green stopper is just above the water surface (i.e., neutrally buoyant). How much ballast water do you need to add to the submarine so it is neutrally buoyant? -Do the calculation (hint: if you are not sure where to begin, draw the submarine and the forces acting on it when it is immersed in water). Check your prediction (calculation) using the ball and syringe provided.
2. Now test your "submarine" in an unknown liquid. What does your observation suggest about the density of the unknown liquid compared to that of water?

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3. Designing Floats

Materials:

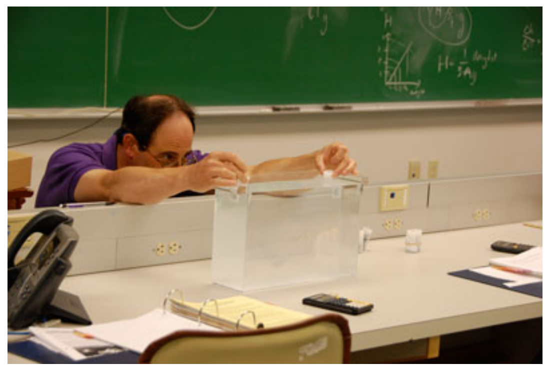
- Containers with freshwater and salt solution
- Two beakers or deep tubs
- Miscellaneous supplies (you don't need to have it all, these are only examples): balloons, rubber bands, film canisters, tape, drinking straws, plastic aquarium tubing, glue guns/ glue, weights (beads, pennies, etc), paper clips, duct tape, bubble wrap, pipe cleaners, syringes, corks, Styrofoam peanuts.
- Scale
- Caliper or ruler
- Graduated cylinder
- An aquarium with stratified fluid (salt and fresh water

Note: salt solution should be the same as in the container of salt water mentioned at the top of this list.

Instructions:

You are funded to carry out a monitoring program off the coast of Maine. Your challenge is to design two autonomous floats that will carry sensors (washers) to measure various hydrographic (e.g., temperature, salinity) and biogeochemical properties (e.g., oxygen, chlorophyll fluorescence, turbidity). One float should be able to drift at the surface. It should float such that its top (the top of the lead) is just above the water surface. The other should remain at the pycnocline (the location where the density changes the most). Your first goal is to design a prototype of the floats, as a proof of concept, to be presented to your program managers (class mates). 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 (what "sensors" they carry, where the sensors are located, etc.) and your approach for determining their buoyancies. You will be asked to test that indeed one of your prototypes remains at the surface and the other remains at the pycnocline in a stratified tank.



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4. Galileo's Thermometer

Materials:

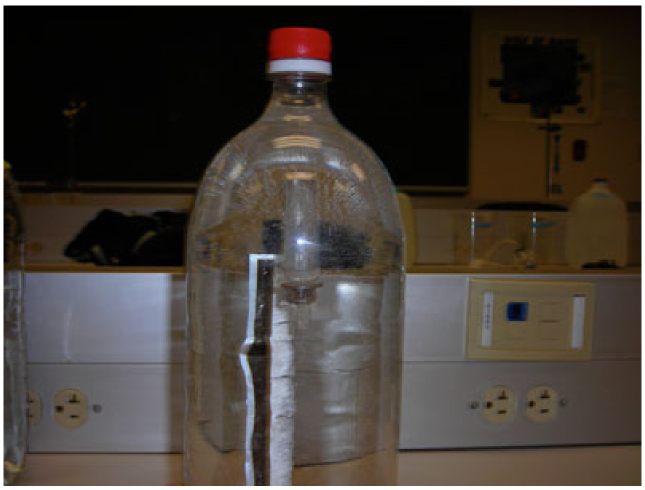
- Galileo's thermometer
- Tub of hot water
- Tub of cold water

Instructions:

Can you explain how this thermometer works (each glass ball has constant volume and mass of colored fluid within it)?

OPTIONAL ACTIVITIES

5. Cartesian Diver



Materials:

- A soda bottle filled with tap water (colored water works best)
- A plastic pipette balanced with a washer

Instructions:

1. Squeeze the bottle. Why is the half closed pipette inside the bottle sinking?
2. How is this behavior related to Archimedes' principle, Pascal's law, and the ideal gas law?

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6. Settling of Particles in Aquatic Environments

Materials:

- Glycerin or clear corn syrup (any brand found in grocery stores).
- Glass beads and steel ball bearings of five different diameters spanning at least O(1 mm) to O(1 cm) (found in hardware stores; (O means order of magnitude). Be careful to obtain glass and steel beads of uniform specific gravity. The larger the range of sizes, the better.
- Two large cylindrical or rectangular settling tanks (note: based on observed and calculated flow patterns around spheres, the cylinder diameter would have to be roughly 100 times the diameter of the settling object to eliminate wall effects. Wall effects will slow the object's terminal sinking velocity, erroneously indicating a greater-than actual fluid viscosity. At the precision sought in this laboratory exercise, a 2-liter graduated cylinder works very well for 1-mm beads and sufficiently well for beads as large as 1 cm)
- A balance
- Stop watch(es)
- Calipers for measuring bead diameter
- Meter stick to measure distance along the cylinder

Optional: thermal setting modeling clay (e.g., SCULPEY, found in craft stores). Divide it in advance to pieces of equal mass.

Instructions:

If an object whose density differs from that of the medium is released, it accelerates upward or downwards, depending on its density relative to that of the medium. After some time, the object will reach a terminal velocity (will move upwards or downwards at a constant velocity). Why?

Part A

1. What are the forces that act on a body?
2. What properties of the fluid and the particle influence settling velocity? For each property indicate whether an increase in that property will result in an increase or a decrease of the settling velocity.

3. Measure the sinking speeds of different diameter beads in Glycerin using a stop watch and a ruler. Measure the sinking speed of each bead at least 3 times to establish some confidence in your measurements. Start-time for a measurement is when the object has reached several centimeters below the surface (at a point where the beads have attained terminal velocity) and stop-time is several centimeters above bottom. Record data in the table below:

Bead diameter (D)/ sinking velocity **in Glycerin**	Sinking velocity (1)	Sinking velocity (2)	Sinking Velocity (3)
D1 =			
D2=			
D3 =			
D4=			

Bead diameter (D)/ sinking velocity **in water**	Sinking velocity (1)	Sinking velocity (2)	Sinking Velocity (3)
D1 =			
D2=			
D3 =			
D4=			

4. Does your prediction in 2 corroborate with your measurements in 3? If not, use your results to revise your answer in 2.

Part B

1. Observe a sample of phytoplankton under the microscope. Why would floatation adaptation or slow sinking rate be important to phytoplankton? What features help phytoplankton slow their sinking velocities?
2. Use the modeling clay to design your own phytoplankton (here we already provide you with some clay models). How does its settling velocity compare to that of a ball of clay of the same mass? Does the orientation of your phytoplankton at the time of release matter?

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BUOYANCY: EXPLANATIONS FOR LAB ACTIVITIES

1. Archimedes' Block

The Archimedes' block has a base that measures 5 cm X 5 cm and its height is 4 cm. Thus, its volume is 100 cm^3 (5 X 5 X 4). The (empty) block weighs 25 g and hence its density is 0.25 g/cm^3.

According to Archimedes principle, when the box is not sinking, nor rising:

$F_{buoyancy} = F_{gravity}$

where $F_{buoyancy} = V_{displaced}\rho_{water}g$ ($V_{displaced}$ is the volume of the displaced water which equals Ah; A is the area of the bottom of the box (5 cm X 5 cm = 25 cm^2), h is the depth of submergence), and $F_{gravity} = mg$ (m is the mass of the box).

Thus,

$Ah\rho_{water}g = mg$ or $h = m/A\rho_{water}$

where the slope of the graph of h, as a function of m, is $1/A\rho_{water} \sim 1/(25\text{cm}^2 \cdot 1\text{gr/cm}^3) = 0.04\text{cm g}^{-1} = 0.4\text{m/Kg}$.

Added mass (gr)	Weight in air	Weight in water	Immersion depth (cm)
0	25	0	1
25	50	0	2
50	75	0	3
75	100	0	4

By Archimedes principle, when the weight of the box exceeds the weight of the displaced water, the box will sink ($F_{buoyancy} = F_{gravity}$ => $m_{displaced}g = m_{box}g$; $m = V\rho$). Because g is constant we will just consider the masses of the box and the displaced water but do not confuse mass with weight (force=mass times g). When the box is fully submerged it displaces its own volume (100 cm^3), thus the weight of the displaced water is 100 g (the mass of 1 cm^3 water is approximately 1 g). When the mass of the box + weights exceeds 100 g it will sink.

The difference between the mass of the box in air and the mass of the displaced water is the mass of the box in the water (sometimes referred to as apparent mass). When you place a mass of 100 g in the box it sinks because its mass in air is now 125 g (box + weights) which is larger than the mass of the displaced water (100 g). The mass of the box in water is therefore 25 g. Have you wondered why objects appear lighter in water? Can you explain it now based on Archimedes' principle?

This activity was deliberately written in a cookbook-style manner to demonstrate that 'hands-on' does not necessarily mean inquiry. Below is an example of how this activity can be presented in an inquiry-based format:

1. Assume that the box is a large cargo ship. As the captain of the ship you need to determine the maximum amount of cargo you can load on your ship without sinking it. Based on what you know about buoyancy (and Archimedes' principle) and the material

available to you, how would you approach this problem? Explain your rationale (hint: think about the weight of an immersed object in the air and in water and the volume it will displace for a given weight. Use the scale and ruler to obtain any measurement that can help you with your prediction).

2. Add the predicted amount of cargo to your ship (box). What is the weight of the ship + cargo (in air). Test you prediction by placing the ship and its cargo in the tub of water and observing if it is fully immersed but not sinking.
3. If your prediction does not support the maximum weight, revise your hypothesis and test it again.

Once you find the maximum cargo, add an additional 25 g to your cargo. What is the weight of the ship + cargo in air? Predict the weight of the (ship + cargo) in water before and after you add the additional mass. Test your hypothesis.

2. Archimedes' Ball

To approach this problem, first calculate the density of the ball (=mass/volume), which is 0.7 g/cm^3, which is less than the density of water (1 g/cm^3). Since the volume of the ball remains constant, the only way to make this ball neutrally buoyant 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. Therefore, 54 g (which equals 54 ml) of tap water must be added to make its density equal to that of water (i.e., neutrally buoyant).

When the ball is placed in the unknown solution, additional water is required to make it neutrally buoyant, indicating that the unknown solution (e.g., salt water) is denser than water.

3. Designing Floats

Comment: if you see that your students take a trial and error approach, encourage them to think in terms of volume, mass, and buoyancy and to conduct the appropriate measurements that will help them to determine the design of their floats (i.e., measure the densities of the fresh and salt water, the mass of the float without 'instruments' and estimate its volume).

4. Galileo's Thermometer

Since the balls inside the thermometer have constant volume (glass is highly incompressible) and mass, their density remains constant. What changes is the density of the surrounding fluid as a result of heating or cooling. The change in relative density between the balls and the surrounding fluid causes them to rise or sink in the column and rearrange according to their densities. The temperature is read from the metal disk attached to each ball; the lowest glass ball of the top set indicates the temperature.

5. Cartesian Diver

A Cartesian diver (named after René Descartes, a French philosopher, mathematician and scientist; the "father of modern philosophy") is a classic science experiment that demonstrates buoyancy (Archimedes' principle) and the ideal gas law. The pipette in the bottle contains an air bubble. When you squeeze the bottle you increase the pressure within the bottle and reduce the volume of the air in the bottle (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, an increase in volume will result in an increase in pressure). Recall Pascal's law: pressure will be transmitted equally, in all directions and to all parts of the fluid. This increases the pressure inside the plastic pipette, results in a decrease in the volume of the air trapped inside the pipette (ideal gas law). This volume is replaced by water. Because the density of water is larger than that of air, the density of the pipette system (pipette+air) increases and sinks.

6. Settling of Particles in Aquatic Environments

A particle in a fluid will sink or rise at a rate that is determined by: its density relative to that of the fluid, its size, its shape, and the viscosity of the fluid. All these factors contribute to the forces that act on the particle. Terminal velocity is reached once all forces are balanced. The discussion below focuses on sinking because it is the primary transport mechanism of carbon from the surface of the ocean to depth. Settling is also an integral part of the life of planktonic organisms that regulate their vertical position with respect to light, nutrients, prey, and predators. (Keep in mind that the same theory applies to rising particles as long as they are rigid. For fluid particles, such as bubbles, the change in volume as a result of changes in pressure also needs to be taken into account.)

What are the forces acting on a settling particle? Three forces act on a particle in a fluid: weight (gravity), buoyancy, and drag.

$$F_{gravity} = mg = \rho_p V_p g$$

where m is the mass of the object, g is the acceleration of gravity ($g = 9.8\ m/s^2$), ρ_p is the density of the particle, and V_p is the volume of the particle.

$$F_{buoyancy} = \rho_f V_p g$$

where ρ_f is the density of the fluid

The net gravitational force:

$$(F_g) = F_{gravity} - F_{buoyancy} = V_p(\rho_p - \rho_f)g$$

For a sphere:

$$V_p = 3\pi r^3/4 = \pi D^3/6$$

where r is the radius of the sphere and D is its diameter

The net gravitational force is downward if the particle is denser than the fluid, and upward if the fluid's density is higher than that of the particle.

F_{drag} has two components:

1. Viscous drag resulting from the difference in velocity between the body and the fluid within which it is immersed.

2. Pressure drag resulting from the spatial variation in pressure between the fore and aft of a settling particle (high in fore; low in aft).

.A particle will reach its terminal velocity when all forces are balanced. In that case, we can compute the drag force from:

$F_{drag} = F_{gravity} - F_{buoyancy}$