NAME PERIOD DATE

2. BUOYANT FORCE

STRUCTURED

Driving Question | Objective

What are the relationships between the buoyant force on an object submerged in a fluid and a) the volume of the submerged object, and b) the weight of the fluid displaced by the submerged object? Perform an experiment whose data will help determine both relationships.

Materials and Equipment

- Data collection system
- PASCO High Resolution Force Sensor with hook[1]
- PASCO Overflow Can[2]
- Brass cylinder
- Aluminum cylinder
- Balance, 0.01-g resolution (1 per class)
- Table clamp or large base
- Support rod, 45-cm (2)
- Right angle clamp
- Thread, 60 cm
- Beaker, 100-mL
- Beaker, 1-L
- Glass stir rod
- Felt-tipped pen with permanent ink
- Liquid dish soap, 3 mL
- Water, 500 mL
- Paper towel, several sheets
- Meter stick

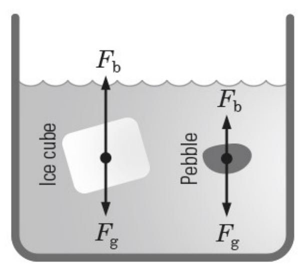
[1]www.pasco.com/ap22

PASCO High Resolution Force Sensor

[2]www.pasco.com/ap25

PASCO Overflow Can

Background



Fluids are generally thought of as liquids; however, this is a common misconception. A fluid is anything that can flow, which includes gasses as well as liquids. When an object is submerged in a fluid, it experiences an upward buoyant force F_b that opposes gravitational force F_g. This is the reason ice floats on the top of water, and a balloon filled with helium rises in air. If we define F_g in the negative direction, a submerged object will rise in the fluid if the net force is positive (the condition of ice rising in water, or a helium balloon rising in air), and sink if it is negative (the condition of a rock sinking in a pond).

The magnitude of the gravitational force acting on an object is proportional to its mass, but it is easily observable that the buoyant force acting on a submerged object is not proportional to the object's mass: a small rock may have the same mass as a tennis ball, but a tennis ball floats in water and the rock does not. So, what is different between these two objects? Their masses may be the same but their volumes are different, and so is the volume of water displaced by each once submerged.

In this activity you will explore the relationship between the buoyant force acting on an object and the volume of fluid displaced by the object, and draw conclusions that help establish the mathematical relationship between buoyant force and a) the volume of the submerged object, and b) the weight of the fluid displaced by the submerged object.

Safety

Follow this important safety precaution in addition to your regular classroom procedures:

- Make necessary arrangements to your workstation to avoid getting water on any electronic equipment.

Procedure

Part 1 – Brass Cylinder

SET UP

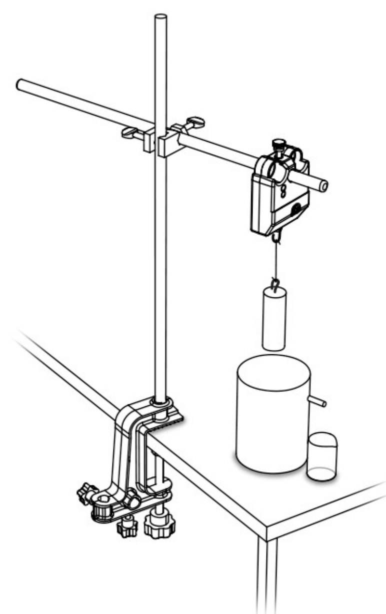
1. Fill the 1-L beaker with approximately 500 mL of water.

2. Slowly add approximately 3 mL of liquid dish soap to the water, and then use the stir rod to slowly mix the soap into the water being very careful not to make the soapy water foamy. Set the soapy water aside for a moment.

3. Use the meter stick to measure the length l and radius r of the brass and aluminum cylinders. Record the values for the brass cylinder in cm in the spaces above Table 1 in the Data Analysis section below. Record the values for the aluminum cylinder in cm above Table 2.

4. Measure and make small marks on the sides of both cylinders at $\frac{1}{4}l$, $\frac{1}{2}l$, and $\frac{3}{4}l$ locations.

5. Assemble your equipment similar to the diagram at right:
   - Use the thread to hang the brass cylinder from the force sensor hook so that it hangs vertically with its top surface approximately 5 cm to 10 cm from the sensor.
   - Place the 100-mL beaker under the spout of the overflow can so it will catch water as it pours out.



6. Connect the high resolution force sensor to the data collection system, and then create a digits display showing Force (Inverted) in newtons.

7. Remove the brass cylinder from the force sensor hook, and then press the Zero button on the force sensor. Rehang the cylinder after the sensor is zeroed.

8. Using the soapy water you just made, slowly fill the overflow can (being very careful not to make the soapy water foamy) until water starts to pour from its spout into the 100-mL beaker. The water will continue to drip into the beaker until it reaches the exact level of the spout inside the can.

9. Once the overflow can has finished dripping, empty the 100-mL beaker into the 1-L beaker, dry the inside of the 100-mL beaker, and place it on the balance.

10. Tare/zero the balance so that it reads zero with the dry 100-mL beaker on it, and then replace the beaker under the spout of the overflow can.

COLLECT DATA

11. Start recording data and observe the force measured by the force sensor. This measured force value is equal to the tension T in the string. Record the first tension value T_1 of the brass cylinder suspended above the water in the overflow can (corresponding to a Depth of 0 m) into Table 1.

12. Gently loosen the thumbscrew on the right angle clamp and slowly lower the cylinder into the water in the overflow can until the cylinder is submerged up to the first mark, $l/4$. Tighten the thumbscrew to hold the cylinder in place as water drips from the overflow can into the 100-mL beaker.

13. Once the overflow can has stopped dripping: in Table 1, record the new tension value T_2 from the force sensor, and then place the 100-mL beaker onto the balance and record the mass of the water that was displaced into the beaker.

14. Repeat the previous steps three additional times, lowering the cylinder to depths of $l/2$, $3l/4$, and l (cylinder completely submerged). Record the tension T_n measured by the force sensor and the total mass of the displaced water each time.

    NOTE: Each time the cylinder is lowered, be sure the overflow can has stopped dripping before recording any measurements.

15. Stop recording data.

Part 2 – Aluminum Cylinder

SET UP

16. Raise the brass cylinder out of the overflow can and remove it. Use the thread to hang the aluminum cylinder from the force sensor hook so that it hangs vertically with its top surface approximately 5 cm to 10 cm from the sensor.

17. Pour the soapy water from the 100-mL beaker into the 1-L beaker, place the 100-mL beaker back under the pour spout, and then slowly refill the overflow can from the 1-L beaker until water starts to pour from its spout into the 100-mL beaker.

18. Once the overflow can has finished dripping, empty the 100-mL beaker into the 1-L beaker, dry the inside of the 100- mL beaker, place it on the balance, and then tare/zero the balance so that it reads zero with the dry 100-mL beaker on it. Replace the dry beaker under the spout of the overflow can.

COLLECT DATA

19. Follow the same Part 1 data collection steps using the aluminum cylinder. Record tension T_n measured by the force sensor and the total mass of the displaced water at the same five depths: 0, $l/4$, $l/2$, $3l/4$, and l (cylinder completely submerged). Record all values using the aluminum cylinder into Table 2.

Data Analysis

Part 1 – Brass Cylinder

Brass cylinder length l (cm): ______________________________

Brass cylinder radius r (cm): ______________________________

Brass cylinder area A_{cyl} (cm²): ______________________________

Table 1: Buoyant force and displacement values for a brass cylinder submerged in a fluid

Depth (cm)		V_{subm} (cm³)	Tension (N)		m_{disp} (g)	F_b (N)	w_{disp} (N)
0	0.00	0.00	T_1		0.00	0.00	0.00
$\frac{1}{4}l$			T_2				
$\frac{1}{2}l$			T_3				
$\frac{3}{4}l$			T_4				
l			T_5				

Part 2 – Aluminum Cylinder

Aluminum cylinder length l (cm): ____________________________

Aluminum cylinder radius r (cm): ____________________________

Aluminum cylinder area A_{cyl} (cm²): ____________________________

Table 2: Buoyant force and displacement values for an aluminum cylinder submerged in a fluid

Depth (cm)		V_{subm} (cm³)	Tension (N)		m_{disp} (g)	F_b (N)	w_{disp} (N)
0	0.00	0.00	T_1		0.00	0.00	0.00
$\frac{1}{4}l$			T_2				
$\frac{1}{2}l$			T_3				
$\frac{3}{4}l$			T_4				
l			T_5				

1. Calculate the following using the measured values for each cylinder. Record the results into or above each cylinder's respective table.

   a. The depth in centimeters in Tables 1 and 2 using cylinder length l.

   b. The cross-sectional area A, in cm^2, of each cylinder using radius r.

   $$A_{\mathrm{cyl}} = \pi r^2$$

   c. The volume of the cylinder submerged V_{subm}, in cm^3, at each depth.

   $$V_{\mathrm{subm}} = \mathrm{depth} \times A_{\mathrm{cyl}}$$

2. If the tension T_{n} measured when each cylinder was submerged is equal to the difference between the gravitational force and the buoyant force:

   $$T_{\mathrm{n}} = F_{\mathrm{g}} - F_{\mathrm{b}}$$

   and the tension T_1 measured when each cylinder was suspended above the water is equal to the gravitational force:

   $$T_1 = F_{\mathrm{g}}$$

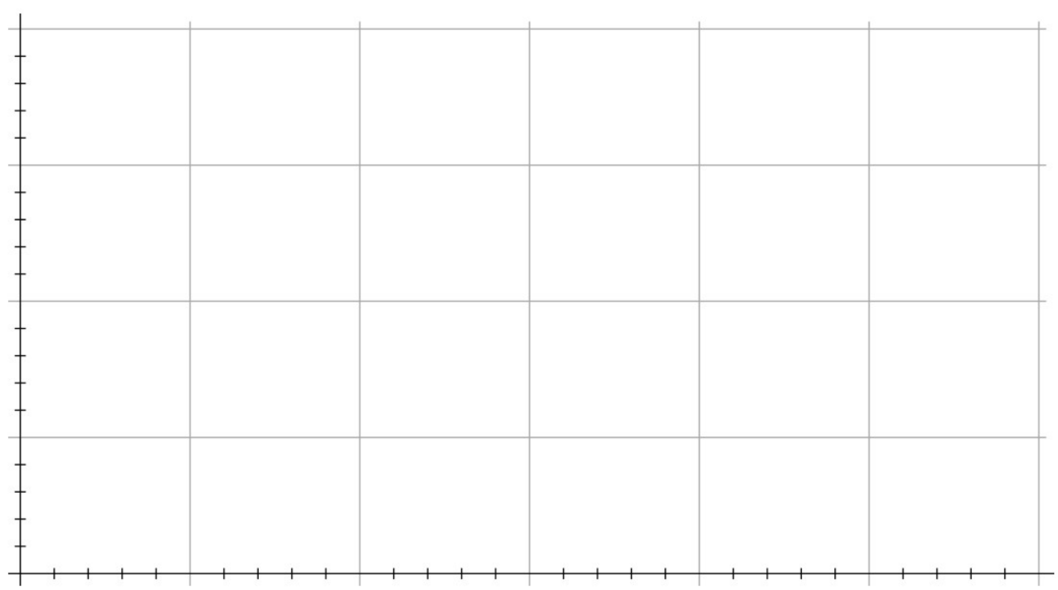
   then the buoyant force on each cylinder is equal to:

   $$F_{\mathrm{b}} = T_1 - T_{\mathrm{n}} \tag{1}$$

   For both cylinders, use Equation 1 to calculate the buoyant force F_{b} at each depth. Record the results into each cylinder's respective table.

3. In the blank Graph 1 axes, plot a graph of *buoyant force* versus *submerged volume* with two curves: one for the brass cylinder and one for the aluminum cylinder. Be sure to label both curves and both axes with the correct scale and units.

Graph 1: Buoyant force on a cylinder versus volume of cylinder submerged



4. Are the curves for the brass and aluminum cylinders in Graph 1 similar?

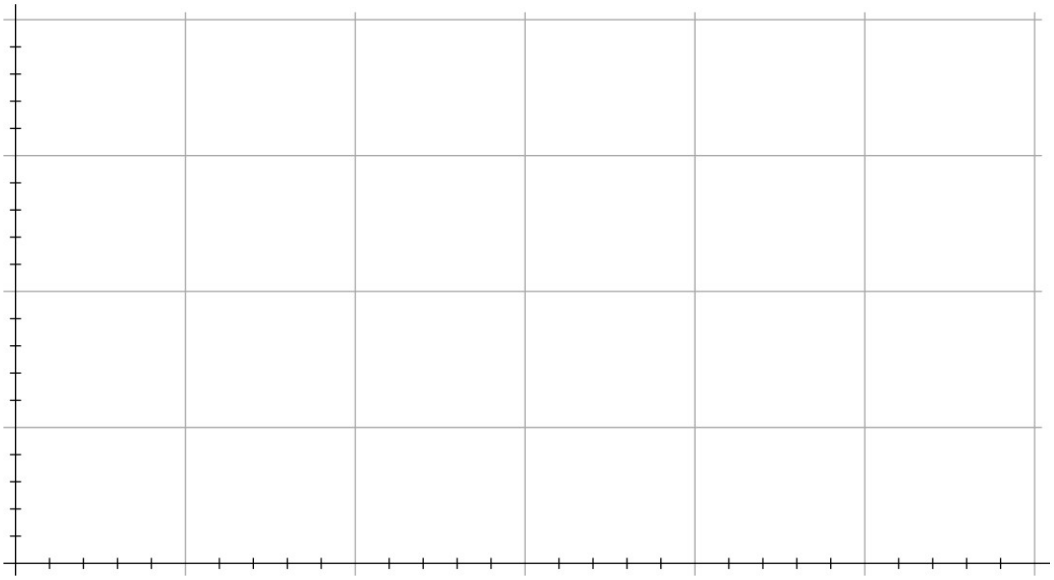
5. Based on your data, is it reasonable to assume that the relationship between buoyant force and submerged volume would be similar if you had used a third object with greater mass (greater density)? Explain your reasoning.

6. Calculate the weight w_{disp} (in newtons) of the displaced fluid at each depth for both cylinders. Record your results into their respective columns.

$$w_{\text{disp}} = m_{\text{disp}} g \times \frac{1\ \text{kg}}{1{,}000\ \text{g}}$$

7. In the blank Graph 2 axes, plot a graph of *buoyant force* versus *weight of displaced fluid* with two curves: one for the brass cylinder and one for the aluminum cylinder. Be sure to label both curves and both axes with the correct scale and units.

Graph 2: Buoyant force on a cylinder versus weight (in newtons) of fluid displaced by the cylinder



8. Are the curves for the brass and aluminum cylinders in Graph 2 similar?

9. Based on your data, is it reasonable to assume that the relationship between buoyant force and the weight of the displaced fluid would be similar for a third object with greater mass (greater density)? Explain your reasoning.

Analysis Questions

1. What type of mathematical relationship (proportional, squared, inverse, inverse squared, et cetera) between buoyant force and submerged volume is implied by your data?

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2. Based on your data, express the relationship between buoyant force F_b and submerged volume V_{subm} by completing this proportionality statement:

$F_b \propto$ ____________________

3. Convert the proportionality statement from the previous question into an equation by introducing a proportionality constant k:

$F_b =$ ____________________

4. The buoyant force F_b acting on an object that is partially or completely submerged in a fluid is described by the equation:

$$F_b = \rho V g \qquad (2)$$

where V is the submerged volume of the object and ρ is the density of the fluid in which the object is submerged. Which terms from this equation would be represented in your equation's proportionality constant k?

$k =$ ____________________

5. Use your data to determine an experimental value for the proportionality constant k. How does this value compare to the theoretical value of the constant in Equation 2? If the experimental value is different from the theoretical value, what caused the difference?

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6. Archimedes's principle states that an object completely or partially submerged in a fluid experiences an upward buoyant force equal in magnitude to the weight of the fluid displaced by the object. Does your data support this statement? If yes, explain how it supports it; if no, identify which data do not support it, and what may have caused this disagreement.

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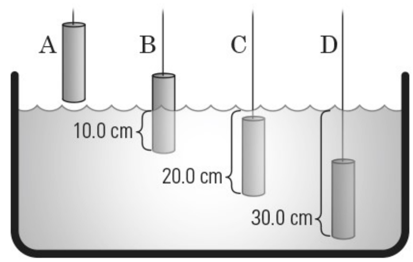
Synthesis Questions

1. A wood salvage company is hoisting an old tree trunk off the bottom and out of a lake. The cable from the hoist is tied around the log above its center of mass. The hoist applies a force of 9,800 N to the cable to suspend the log in the lake water (T_{water}), and a force of 29,000 N to suspend the log above the lake surface (T_{air}). What are the volume and density of the log? Assume the lake water has a density of 1,007 kg/m^3.

2. A cylinder with radius 5.00 cm and length 20.0 cm is lowered into a tank of glucose, which has a density of 1,385 kg/m^3. The cylinder is lowered in four stages:



   A) Zero submersion

   B) Half-submerged to a depth of 10.0 cm

   C) Fully submerged to a depth of 20.0 cm

   D) Fully submerged to a depth of 30.0 cm

   a. What is the buoyant force on the cylinder at each stage?

   b. After being lowered to a depth of 30.0 cm, the string holding the cylinder is cut. If the net force on the cylinder after the string is cut is 1.00 N downward, what is the density of the cylinder material?

3. A crab fisherman has built a crab trap out of plastic pipe and wire mesh. The overall mass and volume of the trap are 5.59 kg and 6,213 cm^3, respectively. To catch crab, the trap must sink to the ocean floor. The fisherman has several lead weights to add to the trap to ensure it sinks. If sea water has a density of 1,021 kg/m^3, and each lead weight has mass of 113.4 g and volume of 10.0 cm^3, what is the minimum number of weights the fisherman must add so that the trap sinks to the ocean floor?