PHYS 2LB: Lab 3
Buoyancy
(Includes Pre-Lab Assignment)

Objectives

These lab activities will focus on the concept of buoyancy and how objects fully or partially immersed in a fluid experience buoyant force. You should read all the steps in each part before you start. Work in your assigned groups and maintain a collaborative and communicative team.

For the following activities, you will use a physics simulation program. Visit: https://uglabs.physics.ucr.edu/ for lab downloads and links.

Introduction

Archimedes, the mathematician, physicist, and engineer, was born around 287 BC in Syracuse, the son of Phidias, an astronomer. Archimedes studied in Alexandria before returning to his native Sicily. His experiments led to what we now know as “Archimedes’ Principle”, which states that a body immersed in fluid loses as much weight as the weight of the liquid it displaces. Understanding the displacement of water in this manner, Archimedes famously demonstrated that the king’s crown was not made of solid gold. Archimedes is also credited with many other notable achievements in physics and mathematics such as the principle of the lever, the discovery of π, and more. Archimedes was killed during the siege of Syracuse in 212 BC.

When we jump into a swimming pool, we all feel lighter; this is due to buoyant force. It is a consequence of the fact that our body is taking up space that was formerly water. When an object is completely submerged in a fluid, all parts of the object experience fluid pressure. The fluid pressure increases with the depth
of the immersion in the fluid. A schematic illustration of the effect is shown in the figure below acting on a simple rectangular prism.

The top surface of the submerged object supports all the liquid above it, so:

\[ F_{\text{top}} = \left( \rho_{\text{fluid}} \cdot g \cdot h_1 \right) \cdot A \]

where \( \rho_{\text{fluid}} \) is the density of the fluid, \( g \) is the acceleration due to gravity, \( h_1 \) is the depth of the fluid to the top surface of the object, and \( A \) is the surface area at the top of the object. The pressure is greater at the bottom of the object simply because \( h_2 > h_1 \), and the force there is:

\[ F_{\text{bottom}} = -\left( \rho_{\text{fluid}} \cdot g \cdot h_2 \right) \cdot A \]

Note that the force at the bottom of the object opposes the direction of the force at the top of the object. Given that \( h_2 > h_1 \), the force acting upwards on the bottom of the object is larger than the force acting downwards on the top of the object. Of course, given Newton’s 2nd Law, the sum of the forces on the object must equal zero since the object is stationary, so the weight of the displaced fluid is the equalizing term:

\[ \Sigma F = F_{\text{bottom}} - F_{\text{top}} - F_g = 0 \]

We can calculate the net force from the fluid acting on the object, which we call the “Buoyant Force” \( (F_B) \):

\[ F_B = F_{\text{bottom}} - F_{\text{top}} = \rho_{\text{fluid}} \cdot g \cdot A \cdot (h_2 - h_1) = \rho_{\text{fluid}} \cdot g \cdot V \quad (\text{Eq. 1}) \]
where \( V = (h_2 - h_1)A \) is the volume of the fluid displaced by the object. This buoyant force is equal and opposite to the force exerted on the displaced fluid by gravity. Archimedes’ Principle applies to all types of fluids (both liquids and gases). Note that it also applies to floating objects, where \( F_{top} \approx 0 \). In today’s lab you will be studying how Archimedes’ Principle applies to objects either fully submerged in or floating on water.

We will be measuring the weight of objects when they are outside of the fluid and when they are submerged inside the fluid. The buoyant force is simply the difference in weight of the cylinder out of the water, \( W_o \), and the weight when the cylinder is \textit{completely submerged} in the water, \( W_i \), or:

\[
F_B = W_o - W_i \quad (E\text{q}. \ 2)
\]

From the measured value of \( F_B \), we can easily calculate the volume, \( V \), using Archimedes’ Principle where \( \rho_{\text{fluid}} = 1,000 \text{ kg/m}^3 \) for water and \( g = 9.8 \text{ m/s}^2 \). In this case, the volume of the displaced water is equal to the volume of the metal cylinder. Knowing the mass and volume of the metal cylinder, its density can be calculated (\( \rho = m/V \)).

When an object floats, this means that the buoyant force is balancing out the force due to gravity on the object, or in mathematical form:

\[
F_B = F_g
\]

This means that since we know the buoyant force depends on the volume of the fluid displaced, \( V_{\text{displaced}} \), and the density of the fluid, that this equation becomes:

\[
\rho_{\text{fluid}} \cdot g \cdot V_{\text{displaced}} = m_{\text{object}} \cdot g
\]

Since the mass of the object is just the density of the object multiplied by the volume of the object, we can get a ratio of the volume displaced by the object to the volume of the object, \( V_{\text{object}} \):

\[
\frac{V_{\text{displaced}}}{V_{\text{object}}} = \frac{\rho_{\text{object}}}{\rho_{\text{fluid}}} \quad (E\text{q}. \ 3)
\]
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Experimental Apparatus:

A screenshot of the simulation used in this lab appears below:

Summary:

This lab is divided into two sections. In the first you will measure the buoyant force on several blocks made out of the same material but having different volumes.

In the second section, you will study how Archimedes’ Principle applies to an object floating in water. Using wood and ice blocks, you will directly measure what percentage of the block is below the water level. You will compare this fraction to that which is predicted by Archimedes’ Principle.
1. Experimental Validity of Archimedes’ Principle

1.1: Change the density of the block (the simulation calls it a “body”) to that of aluminum (2.7 g/cm³), and make sure the density of the liquid is set to that of water (1.0 g/cm³). Also record the volume and weight of the block.

<table>
<thead>
<tr>
<th>Base area of body:</th>
<th>100 cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of body:</td>
<td>5 cm</td>
</tr>
<tr>
<td>Density of body:</td>
<td>2.7 g/cm³</td>
</tr>
<tr>
<td>Density of liquid:</td>
<td>1.0 g/cm³</td>
</tr>
</tbody>
</table>

1.2: Assuming the block will be completely submerged when placed in the central pool of water, use the volume of block and the density of water to calculate the buoyant force on the block, \( F_B \).

1.3: The block is hanging from a force sensor, which is effectively a hanging scale. You should see that the weight of the block and the measured force are identical on the right side of the simulation. Lower the block into the central pool of water until it is completely submerged. Record the effective weight (the “Measured force”) of the block. Does your buoyant force calculated in 1.2 agree with that given by the simulation now that the block is submerged?

1.4: Place the aluminum block back on the land and alter its volume to 1.5 L. Repeat steps 1.1 to 1.3 with this new value for volume.

1.5: Place the aluminum block back on the land and alter its volume to 2.5 L. Repeat steps 1.1 to 1.3 with this new value for volume.

1.6: Record the results of your previous steps in a table with the following columns. Column 1 (V) is the volume of the block, column 2 (\( W_o \)) is the weight of the block outside of the fluid, column 3 (\( W_i \)) is the weight of the block inside of the fluid, and column 4 (\( F_B \)) is the buoyant force on the block when it is submerged in the fluid.
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<table>
<thead>
<tr>
<th>$V$ ($m^3$)</th>
<th>$W_o$ ($N$)</th>
<th>$W_i$ ($N$)</th>
<th>$F_B$ ($N$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

1.7: Open Excel and create a table and a graph. Enter your $F_B$ and $V$ data into the table. Plot $F_B$ vs $V$ on the graph. Make a copy of the table and graph for your notebook.

1.8: Is the graph linear? Should it be? Why? Calculate what the value of the slope should be using your values from the above table in Eq. 1. Then perform a Linear Fit to your data in Excel. A box should appear indicating the slope of the graph. Record the slope in your notebook.

1.9: Change the aluminum block to a brick block. Repeat steps 1.1 through 1.8.

- **Thought Experiment:** Let’s take this result and apply it to a real situation. A planetary scientist wants to measure the density of an oddly shaped meteorite that has been found. She puts the meteorite on a scale and finds the weight is 120 N. She then submerges it completely in pure water and places it on a scale. She finds the meteorite’s weight is 100 N when underwater. Draw a force diagram for the meteorite when it is being weighed underwater.
  - Using your force diagram, find the volume of the meteorite (in $m^3$).
  - Find the density of the meteorite (in $kg/m^3$). According to the table on the next page, what type of metal is this meteorite likely composed of?
### Buoyancy

<table>
<thead>
<tr>
<th>Metal</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>2.7 x 10³</td>
</tr>
<tr>
<td>Copper</td>
<td>8.9 x 10³</td>
</tr>
<tr>
<td>Gallium</td>
<td>5.9 x 10³</td>
</tr>
<tr>
<td>Gold</td>
<td>1.93 x 10⁴</td>
</tr>
<tr>
<td>Iron</td>
<td>7.9 x 10³</td>
</tr>
<tr>
<td>Lead</td>
<td>1.13 x 10⁴</td>
</tr>
<tr>
<td>Magnesium</td>
<td>1.7 x 10³</td>
</tr>
<tr>
<td>Silver</td>
<td>1.05 x 10⁴</td>
</tr>
<tr>
<td>Tin</td>
<td>7.3 x 10³</td>
</tr>
<tr>
<td>Titanium</td>
<td>4.5 x 10³</td>
</tr>
<tr>
<td>Tungsten</td>
<td>1.92 x 10⁴</td>
</tr>
<tr>
<td>Zinc</td>
<td>7.1 x 10³</td>
</tr>
</tbody>
</table>

2. **Buoyant Force on Floating Objects**

2.1: Set the volume of your block to any value you desire (but keep the height of the block at least 5 cm) and record the value (in m³) in your notebook.

2.2: In this part of the lab, you will use a “wood” block. Set the density of the block to that of a light Oak wood (about 0.6 g/cm³). Record the force of gravity on the block. Calculate and record the block’s density (in kg/m³ from the weight and volume). Compare it to the density you input a moment ago.

2.3: Lower the block into the central pool of water, as low as the simulation will let you (this is the height at which the block would float, you’ll notice that the measured force drops to 0.00 N). Determine what percentage of the block is submerged in the water. The simulation tells you how deep (in cm) the block is submerged in the row labeled “Draught”.
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2.4: Based on the percentage you found in 2.3 and the volume you chose in 2.1, calculate the volume of water displaced by the block. Does this value agree with the “Replaced volume” given by the simulation?

2.5: Using the volume of displaced water and knowing the density of water calculate the buoyant force on the wood. Compare this value to the force of gravity that you found in 2.1 and the buoyant force given by the simulation.

2.6: Change the Density of the liquid in the pool from that of Water to Honey (look up the density of honey) and repeat steps 2.2 through 2.5. Is the buoyant force the same whether you used water or honey as the fluid?

2.7: Change the wood block to an ice block (i.e. look up the density of ice and change the density of the block in the simulation to that of ice) and repeat steps 2.2 through 2.6.

2.8: Did the density of the block of wood and ice have to be less than the density of water in order to float (i.e. not be completely submerged)? Lead has a much greater density than water. How does a boat or ship carrying hundreds of pounds of lead float while that same lead would sink to the bottom of the ocean if dumped overboard?

- Thought Experiment: Now imagine that you were to dump the iron off the side of the boat, would more water be displaced be when the iron was on the boat or when the iron was dumped overboard and now sits in the bottom of the ocean? Explain.
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Pre-Lab Assignment (1 point)

1. A ball is floating (stationary) in a pool of water. 25% of its volume is immersed in the water.
   
a. Draw a force diagram for the ball in this situation.
   
b. What is the density of the ball (in kg/m$^3$)?