Answer to Essential Question 9.5: No. These metal objects are denser than water, so we expect them to sink in the water (which they will if they are not placed carefully at the surface). They are held up by the surface tension of the water. Surface tension is beyond the scope of this book but it is similar to how a gymnast is supported by a trampoline – the water surface can act like a stretchy membrane that can support an object that is not too massive.

9-6 Pressure

Where does the buoyant force come from? What is responsible, for instance, for the small upward buoyant force exerted on us by the air when we are surrounded by air? Let's use a model in which the fluid is considered to be made up of a large number of fast-moving particles that collide elastically with one another and with anything immersed in it. For simplicity, let's examine the effect of these collisions on a block of height *h* and area *A* that is suspended from a light string, as shown in Figure 9.16.

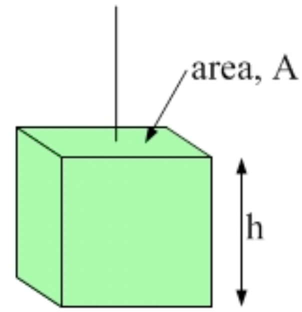

Figure 9.16: A block of height *h* and area *A* supported by a light string.

Consider a collision involving an air molecule bouncing off the left side of the block, as in Figure 9.17. Assuming the block remains at rest during the collision (the block's mass is much larger than that of the air molecule), then, because the collision is elastic, the magnitude of the molecule's momentum remains the same and only the direction changes: the component of the molecule's momentum that is directed right before the collision is directed left after the collision. All other momentum components remain the same. The block exerts a force to the left on the molecule during the collision, so the block experiences an equal-and-opposite force to the right.

There are a many molecules bouncing off the left side of the block, producing a sizable force to the right on the block. The block does not accelerate to the right, however, because there is also a large number of molecules bouncing off the right side of the block, producing a force to the left on the block. Averaged over time, the rightward and leftward forces balance. Similarly, the forces on the front and back surfaces cancel one another.

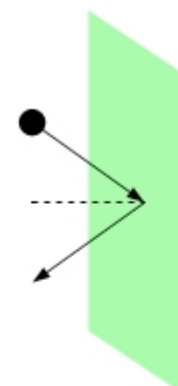

Figure 9.17: A magnified view of a molecule bouncing off the left side of the block.

If all the forces cancel out, how do these collisions give rise to the buoyant force? Consider the top and bottom surfaces of the cube. Because the buoyant force exerted on the cube by the air is directed vertically up, the upward force on the block associated with air molecules bouncing off the block's bottom surface must be larger than the downward force on the block from air molecules bouncing off the block's top surface. Expressing this as an equation, and taking up to be positive, we get:

$$+F_{bottom} - F_{top} = +F_B = +\rho_{fluid} V_{disp} g \,.$$

The volume of air displaced by the block is the block's entire volume, which is its area multiplied by its height: $V_{disp} = Ah$. Substituting $V_{disp} = Ah$ into the expression above gives:

$$+F_{bottom} - F_{top} = +F_B = +\rho_{fluid} A h g \,.$$

This is the origin of the buoyant force – the net upward force applied to the block by molecules bouncing off the block's bottom surface is larger in magnitude than the net downward force applied by molecules bouncing off the block's upper surface. This is a gravitational effect – the buoyant force is proportional to *g*. One way to think about this is that if the molecules at the block's top surface have a particular average kinetic energy, to conserve energy those at the block's bottom surface should have a larger kinetic energy because their gravitational potential energy is less. Thus, molecules bouncing off the bottom surface are more energetic, and they impart a larger average force to the block than the molecules at the top surface.

Dividing both sides of the previous equation by the area A gives:

$$+\frac{F_{bottom}}{A} - \frac{F_{top}}{A} = +\rho_{fluid}\, h\, g\,. \qquad \text{(Equation 9.5)}$$

The name for the quantity of force per unit area is **pressure**.

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} \quad \text{or} \quad P = \frac{F}{A}. \qquad \text{(Equation 9.6: \textbf{Pressure})}$$

The MKS unit for pressure is the pascal (Pa). $1\text{ Pa} = 1\text{ N}/\text{m}^2$.

Using the symbol P for pressure, we can write Equation 9.5 as:

$$P_{bottom} - P_{top} = \rho_{fluid}\, h\, g\,.$$

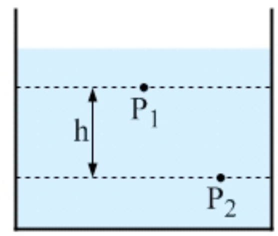

Figure 9.18: The pressure difference between two points is proportional to the vertical distance between them. Pressure increases with depth in a static fluid.

We can write this equation in a general way, so that it relates the pressures of any two points, points 1 and 2, in a static fluid, where point 2 is a vertical distance h below the level of point 1. This gives:

$$P_2 = P_1 + \rho g h\,. \qquad \text{(Equation 9.7: \textbf{Pressure in a static fluid})}$$

As represented by Figure 9.18, only the vertical level of the point matters. Any horizontal displacement in moving from point 1 to point 2 is irrelevant.

EXPLORATION 9.6 – Pressure in the L

Consider the L-shaped container in Figure 9.19. Rank points A, B, and C in terms of their pressure, from largest to smallest.

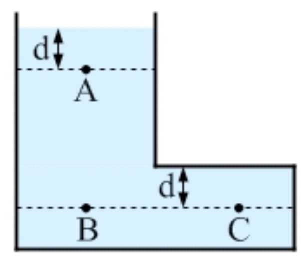

Figure 9.19: A container shaped like an L that is filled with fluid and open at the top.

Because pressure in a static fluid depends only on vertical position, points B and C have equal pressures, and the pressure at that level in the fluid is higher than that at point A. The fact that there is a column of water of height d immediately above both points A and C is irrelevant. The fact that C is farthest from the opening is also irrelevant. Only the vertical position of the points matters.

Key ideas: In a static fluid the pressure at any point is determined by that point's vertical position. All points at the same level have the same pressure, and points lower down have higher pressure than points higher up.
Related End-of-Chapter Exercises: 10, 51.

Essential Question 9.6: Water is placed in a U-shaped tube, as shown in Figure 9.20. The tube's left arm is open to the atmosphere, but the tube's right arm is sealed with a rubber stopper. Rank points A, B, and C based on their pressure, from largest to smallest.

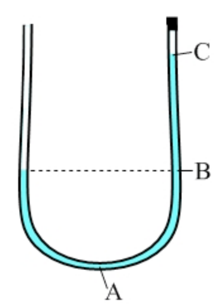

Figure 9.20: A U-shaped water-filled tube that is sealed at the top right by a rubber stopper.