9-1 The Buoyant Force

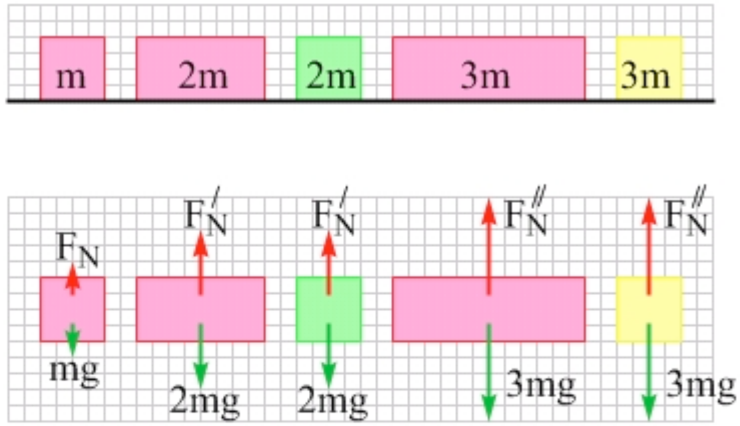


Figure 9.1: A diagram of the blocks we will place in a beaker of water, and the free-body diagram for each block as it sits on a table.

We should begin by defining what a fluid is. Many people think of a fluid as a liquid, but **a fluid is anything that can flow**. By this definition, a fluid can be a liquid or a gas. Flowing fluids can be rather complicated, so let's start with static fluids – fluids that are at rest.

Let's consider some experiments involving various blocks that float in a container of water. The blocks are represented in Figure 9.1, which shows how the masses of the blocks compare, and also shows the free-body diagrams of the blocks as they sit in equilibrium on a table. Starting from the left, the first, second, and fourth blocks are all made from the same material. The other two blocks are both made from different material.

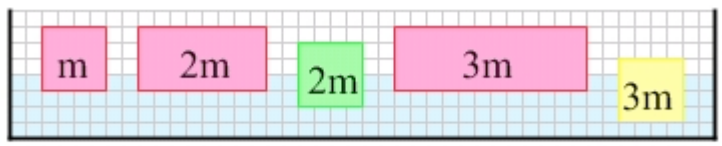
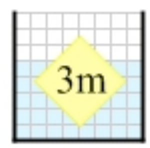


Figure 9.2: A diagram of the blocks floating in the beaker of water.

Our first goal is to look at the similarities between the normal force (a force arising from contact between solid objects) and the force arising from the interaction between an object and a fluid that the object is completely or partly submerged in. Figure 9.2 illustrates how the blocks float when they are placed in the container of water. We have taken some liberties here, because in reality some of the blocks would tilt 45˚ and float as shown in Figure 9.3. Neglecting this rotation simplifies the analysis without affecting the conclusions.

Figure 9.3: We will ignore the fact that blocks that are submerged more than 50% tend to float rotated by 45˚ from the way they are drawn in Figure 9.2. Neglecting this fact will simplify the analysis without affecting the conclusions.



EXPLORATION 9.1 – Free-body diagrams for floating objects

Sketch the free-body diagram of the blocks in Figure 9.2 as they float in the container of water. Note that each block is in equilibrium – what does that imply about the net force acting on each block? Because each block is in equilibrium, the net force acting on each block must be zero.

What forces act on each block? As usual there is a downward force of gravity. Because each block is in equilibrium, however, the net force acting on each block is zero. For now, let's keep things simple and show, on each block, one upward force that balances the force of gravity. The free-body diagrams are shown in Figure 9.4. Note that there is no normal force, because the blocks are not in contact with a solid object. Instead, they are supported by the fluid. We call the upward force applied by a fluid to an object in that fluid **the buoyant force**, which we symbolize as $\vec{F}_B$.

Because the objects are only in contact with the fluid, the fluid must be applying the upward buoyant force to each block. Compare the free-body diagrams in Figure 9.1, when the blocks are in equilibrium on the table, with the free-body diagrams in Figure 9.4, when the blocks

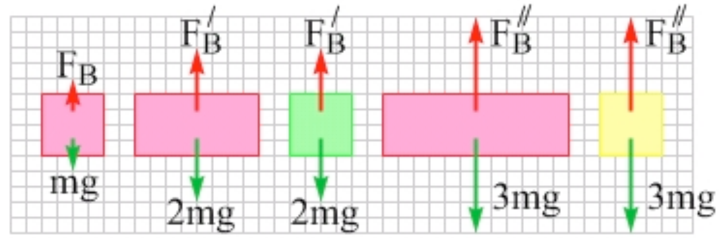


Figure 9.4: Free-body diagrams for the blocks floating in equilibrium in the beaker of water. F_B represents the buoyant force, an upward force applied on each block by the fluid.

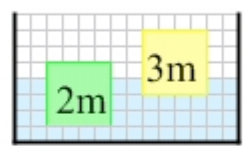
are in equilibrium while floating in the fluid. For a floating object, at least, there are a lot of similarities between the buoyant force exerted by a fluid and the normal force exerted by a solid surface.

Examine Figures 9.2 and 9.4 closely. Even though the two blocks of mass 2*m* are immersed to different levels in the fluid, they displace the same volume of fluid, so they experience equal buoyant forces. The 3*m* blocks displace 50% more volume than do the blocks of mass 2*m*, and they experience a buoyant force that is 50% larger. The block of mass *m*, on the other hand, displaces half the volume of fluid that the blocks of mass 2*m* do, and experiences a buoyant force that is half as large. We can conclude that ***the buoyant force exerted on an object by a fluid is proportional to V_{disp}, the volume of fluid displaced by that object***. We can express this as an equation (where $\propto$ means "is proportional to"),

$$F_B \propto V_{disp} .$$ (Eq. 9.1: **Buoyant force is proportional to volume of fluid displaced**)

Key idea about the buoyant force: An object in a fluid experiences a net upward force we call the buoyant force, $\vec{F}_B$. The magnitude of the buoyant force is proportional to the volume of fluid displaced by the object. **Related End-of-Chapter Exercise: 2.**

The conclusion above is supported by the fact that if we push a block farther down into the water and let go, the block bobs up. The buoyant force increases when we push the block down because the volume of fluid displaced increases, so, when we let go, the block experiences a net upward force. Conversely, when a block is raised, it displaces less fluid, reducing the buoyant force and giving rise to a net downward force when we let go. Figure 9.5 shows these situations and the corresponding free-body diagrams.



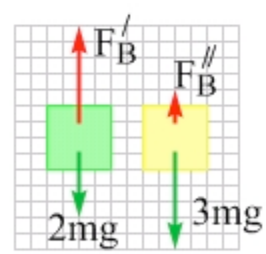


Figure 9.5: In this case, the blocks are not at equilibrium. The block on the left has been pushed down into the water and released. Because it displaces more water than it does at equilibrium, the buoyant force applied to it by the water is larger than the force of gravity applied to it by the Earth and it experiences a net upward force. The reverse is true for the block on the right, which has been lifted up and released. Displacing less water causes the buoyant force to decrease, giving rise to a net downward force.

Figure 9.6: To be able to float, this large ship needs to displace a very large volume of fluid. This large volume of fluid is displaced by the part of the ship that is below the water surface, and which, therefore, is not visible to us in this photograph. Photo credit: by Peter Griffin, from http://www.publicdomainpictures.net..

Essential Question 9.1: Two objects float in equilibrium in the same fluid. Object A displaces more fluid than object B. Which object has a larger mass?