19.2 Buoyancy

If you have ever lifted a submerged object out of water, you are familiar with **buoyancy,** the apparent loss of weight of objects when submerged in a liquid. It is a lot easier to lift a boulder submerged on the bottom of a riverbed than to lift it above the water's surface. The reason is that when the boulder is submerged, the water exerts an upward force that is opposite in direction to gravity. This upward force is called the **buoyant force.**

To understand where the buoyant force comes from, look at Figure 19.6. The arrows represent the forces within the liquid that produce pressure against the submerged boulder. The forces are greater at greater depth. The forces acting horizontally against the sides cancel each other, so the boulder is not pushed sideways. But the forces acting upward against the bottom are greater than those acting downward against the top because the bottom of the boulder is deeper. The difference in upward and downward forces is the buoyant force.

When the weight of a submerged object is greater than the buoyant force, the object will sink. When the weight is equal to the buoyant force, the submerged object will remain at any level, like a fish. When the weight is less than the buoyant force, the object will rise to the surface and float.

To further understand buoyancy, it helps to think more about what happens when an object is placed in water. If a stone is placed in a container of water, the water level will rise (Figure 19.7). Water is said to be **displaced,** or pushed aside, by the stone. A little thought will tell us that the volume—that is, the amount of space taken up or the number of cubic centimeters—of water displaced is equal to the

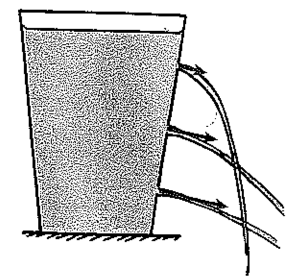


Figure 19.5 ▲
(Top) The forces in a liquid that produce pressure against a surface add up to a net force that is perpendicular to the surface. (Bottom) Liquid escaping through a hole initially moves perpendicular to the surface.

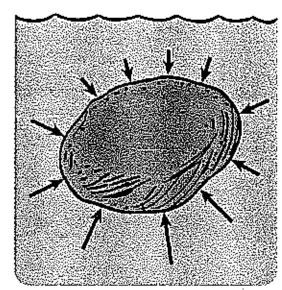


Figure 19.6 ▲
The upward forces against the bottom of a submerged object are greater than the downward forces against the top. There is a net upward force, the buoyant force.

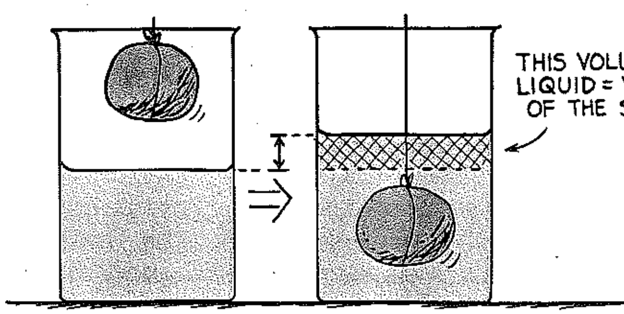


Figure 19.7 ▲
When an object is submerged, it displaces a volume of water equal to the volume of the object itself.

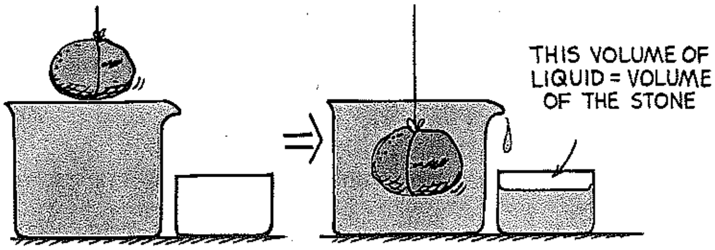


Figure 19.8 ▲
When an object is submerged in a container that is initially brim full, the volume of water that overflows is equal to the volume of the object itself.

volume of the stone. *A completely submerged object always displaces a volume of liquid equal to its own volume.*

This gives us a good way to determine the volume of an irregularly shaped object. Simply submerge it in water in a measuring cup and note the apparent increase in volume of the water. That increase is equal to the volume of the submerged object. You'll find this technique handy whenever you want to determine the density of things like rocks that have irregular shapes.

19.3 Archimedes' Principle

The relationship between buoyancy and displaced liquid was discovered in ancient times by the Greek philosopher Archimedes (third century B.C.). It is stated as follows:

> An immersed object is buoyed up by a force equal to the weight of the fluid it displaces.

This relationship is called **Archimedes' principle.** It is true for liquids and gases, which are both fluids.

Immersed means "either completely or partially submerged." For example, if we immerse a sealed 1-liter container halfway into water, it will displace half a liter of water and be buoyed up by the weight of half a liter of water. If we immerse it all the way (submerge it), it will be buoyed up by the weight of a full liter of water (9.8 newtons). Unless the completely submerged container becomes compressed, the buoyant force will equal the weight of 1 liter of water at *any* depth.* Why? Because the container will displace the same volume of water, and hence the same weight of water, at any depth. The weight of this displaced water (not the weight of the submerged object!) is the buoyant force.

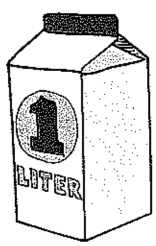


Figure 19.9 ▲
A liter of water occupies 1000 cubic centimeters, has a mass of 1 kilogram, and weighs 9.8 N. Any object with a volume of 1 liter will experience a buoyant force of 9.8 N when fully submerged in water.

A 300-gram brick weighs about 3 N in air. Suppose the brick displaces 2 N of water when it is submerged (Figure 19.10). The buoyant force on the submerged brick will also equal 2 N. The brick will seem to weigh less under water than above water. In the water, its apparent

* Water is practically incompressible. A liter of water under great pressure far below the surface still weighs almost the same as a liter of water near the surface, approximately 9.8 N.

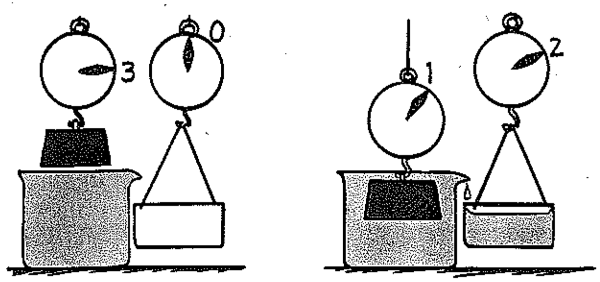


Figure 19.10
A brick weighs less in water than in air. The buoyant force on the submerged brick is equal to the weight of the water displaced. So the brick appears lighter under water by an amount equal to the weight of water (2 N) that has spilled into the smaller container. The apparent weight of the brick under water equals its weight in air minus the buoyant force (3 N − 2 N = 1 N).

weight will be 3 N minus the 2-N buoyant force, or 1 N. The apparent weight of a submerged object is its weight in air minus the buoyant force.

You can summarize Archimedes' principle by way of a numerical example. Show that the upward force due to water pressure on the bottom of a submerged block, minus the downward force due to water pressure on the top, equals the weight of liquid displaced. As long as the block is submerged, depth makes no difference. Why? Because although there is more pressure at greater depths, the *difference* in pressures on the bottom and top of the block is the same at any depth (Figure 19.11). Whatever the shape of a submerged object, the buoyant force equals the weight of liquid displaced.

19.4 Does It Sink, or Does It Float?

We have learned that the buoyant force on a submerged object depends on the object's volume. A smaller object displaces less water so a smaller buoyant force acts on it. A larger object displaces more water so a larger buoyant force acts on it. The submerged object's *volume*—not its *weight*—determines buoyant force. (A misunderstanding of this idea is at the root of a lot of confusion that you or your friends may have about buoyancy!)

So far we've focused on the weight of displaced fluid, not the weight of the submerged object. Now we consider its role.

Whether an object sinks or floats (or does neither) depends on both its buoyant force (up) and its weight (down)—how great the buoyant force is compared *with the object's weight.* Careful thought will show that when the buoyant force exactly equals the weight of a completely submerged object, then the object's weight must equal the weight of displaced water. Since the volumes of the object and of the displaced water are the same, the density of the object must equal the density of water.

This is true for a fish, whose density equals the density of water. The fish is "at one" with the water—it doesn't sink or float. If the fish were somehow bloated up, it would be less dense than water, and would float to the top. If the fish swallowed a stone and became more dense than water, it would sink to the bottom.

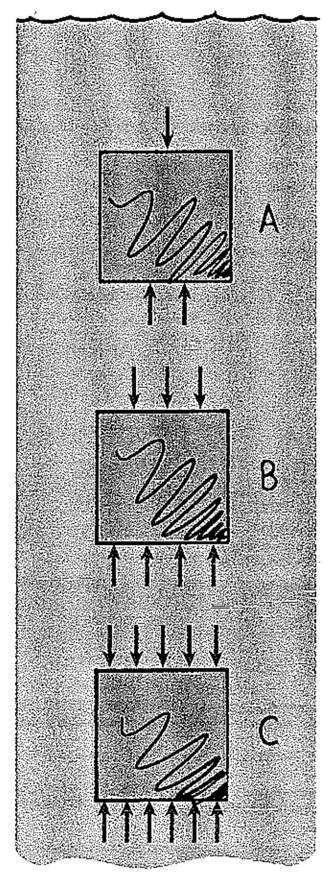


Figure 19.11 ▲
The difference in the upward and downward force acting on the submerged block is the same at any depth.

This can be summed up in three simple rules.

1. An object more dense than the fluid in which it is immersed sinks.
2. An object less dense than the fluid in which it is immersed floats.
3. An object with density equal to the density of the fluid in which it is immersed neither sinks nor floats.

From these rules, what do we say about people who, try as they may, cannot float?* They're simply too dense! To float more easily, you must reduce your density. Since weight density is weight divided by volume, you must either reduce your weight or increase your volume. Taking in a lung full of air can increase your volume (temporarily!). A life jacket does the job better. It increases volume while adding little to your weight.

The density of a submarine is controlled by the flow of water into and out of its ballast tanks. In this way the weight of the submarine can be varied to achieve the desired average density. A fish regulates its density by expanding or contracting an air sac that changes its volume. The fish can move upward by increasing its volume (which decreases density) and downward by contracting its volume (which increases density). A crocodile increases its density when it swallows stones. From 4 to 5 kg of stones have been found lodged in the front part of the stomach in large crocodiles. With its increased density, the crocodile swims lower in the water and exposes less of itself to its prey.

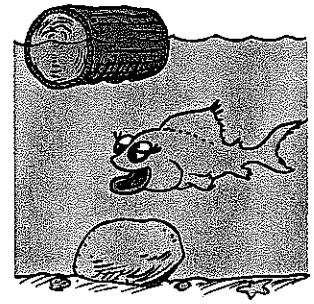
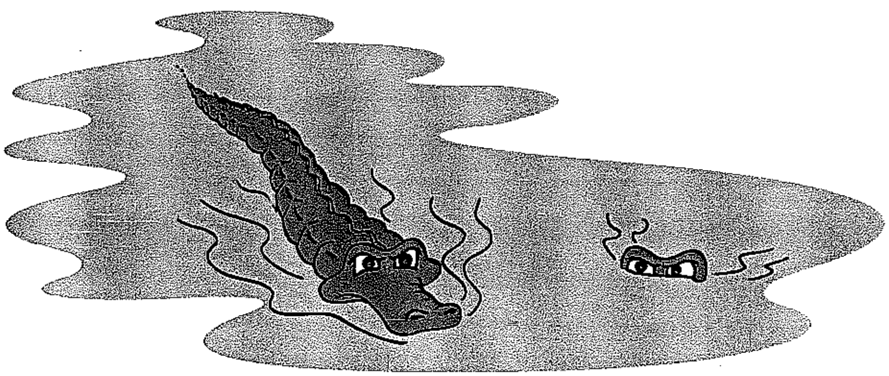


Figure 19.12 ▲
The wood floats because it is less dense than water. The rock sinks because it is more dense than water. The fish neither rises nor sinks because it has the same density as water.



◀ **Figure 19.13**
(Left) A crocodile coming toward you in the water. (Right) A crocodile with a belly full of stones coming toward you in the water.

19.5 Flotation

Primitive peoples made their boats of wood. Could they have conceived of an iron ship? We don't know. The idea of floating iron might have seemed strange. Today it is easy for us to understand how a ship made of iron can float.

Consider a solid 1-ton block of iron. Iron is nearly eight times as dense as water, so when it is submerged, it will displace only 1/8 ton of water. The buoyant force will be far from enough to keep it from sinking. Suppose we reshape the same iron block into a bowl shape, as shown in Figure 19.14. The iron bowl still weighs 1 ton. If you lower the bowl into a body of water, it displaces a greater volume of water than before. The deeper the bowl is immersed, the more water is displaced and the greater is the buoyant force exerted on the bowl. When the weight of the displaced water equals the weight of the bowl, it will sink no farther. It will float because the buoyant force now equals the weight of the bowl.

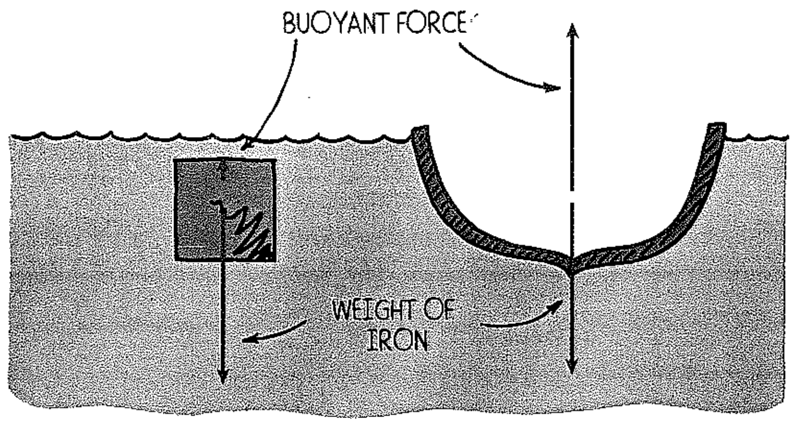


Figure 19.14 ▲
A solid iron block sinks, while the same block shaped to occupy at least eight times as much volume floats.

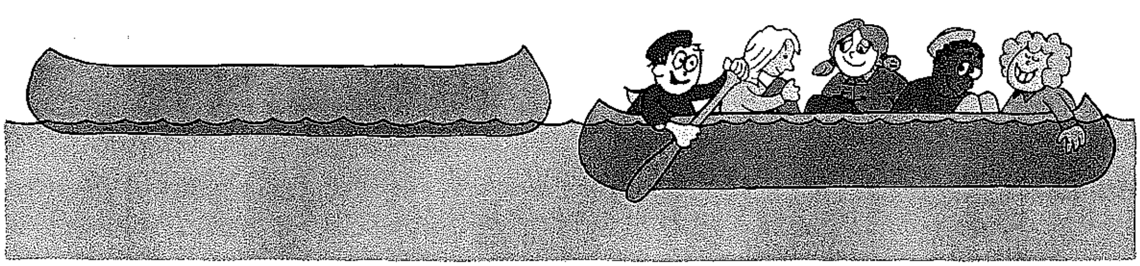


Figure 19.15 ▲
The weight of a floating object equals the weight of the water displaced by the submerged part.

This is an example of the **principle of flotation,** which states,*

> A floating object displaces a weight of fluid equal to its own weight.

Every ship must be designed to displace a weight of water equal to its own weight. Thus, a 10 000-ton ship must be built wide enough to displace 10 000 tons of water before it sinks too deep below the surface.

Think about a submarine beneath the surface. If it displaces a weight of water greater than its own weight, it will rise. If it displaces less, it will go down. If it displaces exactly its weight, it will remain at constant depth. Water has slightly different densities at different temperatures, so a submarine must make periodic adjustments as it moves through the ocean. As the next chapter shows, a hot-air balloon obeys the same rules.

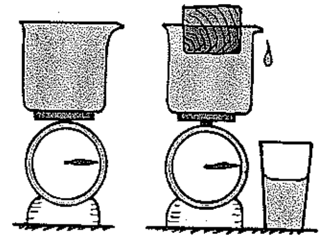


Figure 19.16 ▲
A floating object displaces a weight of liquid equal to its own weight.

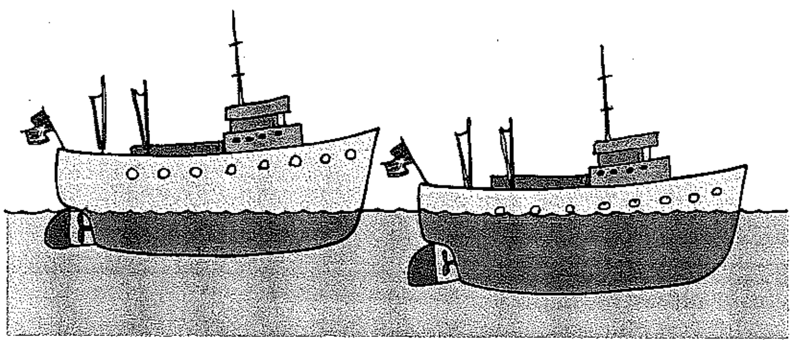


Figure 19.17 ▲
The same ship empty and loaded. How does the weight of its load compare with the weight of extra water displaced?

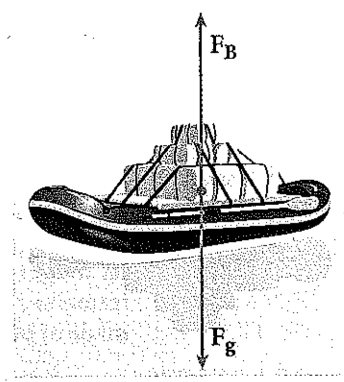


Figure 3
The raft and cargo are floating because their weight and the buoyant force are balanced.

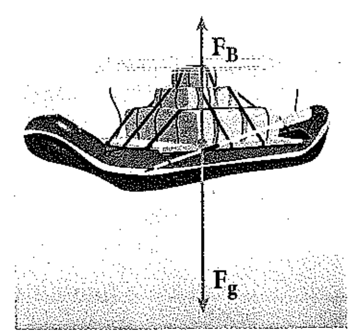


Figure 4
The raft and cargo sink because their density is greater than the density of water.

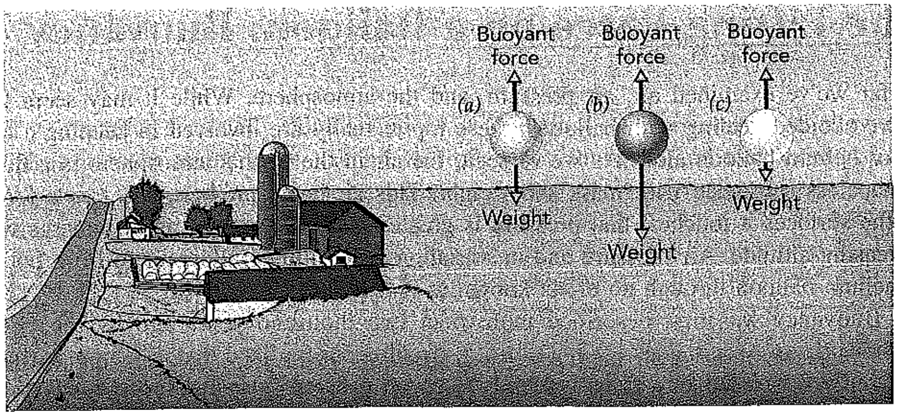


Fig. 5.1.3 (*a*) A portion of air immersed in that same air experiences an upward buoyant force equal to its weight and doesn't accelerate. (*b*) An object that is heavier than the air it displaces sinks, while (*c*) another object that is lighter than the air it displaces floats.

Hot-Air Balloons

Since air is very light, with a density of only 1.25 kg/m^3 (0.078 lbm/ft^3), few objects float in it. One of these rare objects is a perfectly empty balloon. Assuming that the balloon has a very thin outer shell or *envelope,* it will weigh almost nothing and have an average density near zero. Because its negligible weight is less than the upward buoyant force it experiences, the empty balloon will float upward nicely.

Unfortunately, this empty balloon won't last long. Because it's surrounded by atmospheric pressure air, each square meter of its envelope will experience an inward force of 100,000 N. With nothing inside the balloon to support its envelope against this crushing force, it will smash flat. A thick, rigid envelope might be able to withstand the pressure of the surrounding air, but then the balloon's average density would be large and it would sink. So an empty balloon won't work.

What will work is a balloon filled with something that exerts an outward pressure on the envelope equal to the inward pressure of the surrounding air. Then each portion of the envelope will experience zero net force and the balloon will not be crushed. We could fill the balloon with outside air, but that would make its average density too high. Instead, we need a gas that has the same pressure as the surrounding air but a lower density.

One gas that has a lower density at atmospheric pressure is hot air. Filling our balloon with hot air takes fewer particles than filling it with cold air, since each hot-air particle is moving faster and contributes more to the overall pressure than does a cold-air particle. A hot-air balloon contains fewer particles, has less mass, and weighs less than it would if it contained cold air. Now we have a practical balloon with an average density less than that of the surrounding air. The buoyant force it experiences is larger than its weight, and up it goes (Fig. 5.1.4).

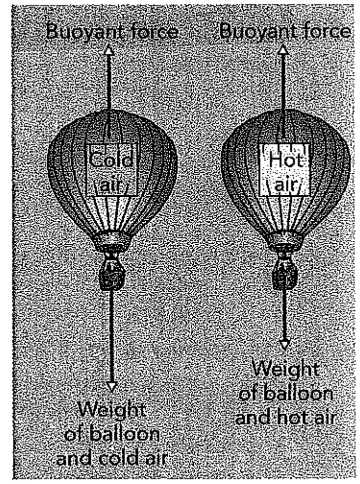
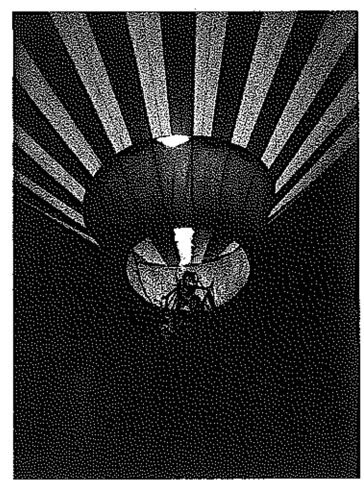


Fig. 5.1.4 A balloon filled with hot air contains fewer air particles and weighs less than a balloon filled with cold air. If the balloon's weight is small enough, the net force on the balloon will be in the upward direction and the balloon will accelerate upward.

Because the air pressure inside a hot-air balloon is the same as the air pressure outside the balloon, the air has no tendency to move in or out (an issue we will cover in the next section), and the balloon doesn't need to be sealed (Fig. 5.1.5). A large propane burner, located beneath the balloon's open end, heats the air that fills the envelope. The hotter the air in the envelope, the lower its density and the less the balloon weighs. The balloon's pilot controls the flame so that the balloon's weight is very nearly equal to the buoyant force on the balloon. If the pilot raises the air's temperature, particles leave the envelope, the balloon's weight decreases, and the balloon rises. If the pilot allows the air to cool, particles enter the envelope, the balloon's weight increases, and the balloon descends.



Courtesy Lou Bloomfield

Fig. 5.1.5 The bottom of a hot-air balloon is open so that heated air can flow in and cold air can flow out. The heated air displaces more than its weight in cold air and makes the balloon lighter.

But even if the pilot heats the air very hot, the balloon won't rise upward forever. As the balloon ascends, the air becomes thinner and the pressure decreases both inside and outside the envelope. Although the balloon's weight decreases as the air thins out, the buoyant force on it decreases even more rapidly, and it becomes less effective at lifting its cargo. When the air becomes too thin to lift the balloon any higher, the balloon reaches a *flight ceiling* above which it can't rise, even if the pilot turns the flame on full blast. For each hot-air temperature, then, there is a cruising altitude at which the balloon will hover. When the balloon reaches that altitude, it's in a stable equilibrium. If the balloon shifts downward for some reason, the net force on it will be upward; if it shifts upward, the net force on it will be downward.