4.2 Buoyancy

If you drop a steel marble into a glass of water, it sinks to the bottom. The steel does not float because it has a greater density than the water. And yet many ships are made of steel. How does a steel ship float when a steel marble sinks? The answer has to do with gravity and weight.

Weight and buoyancy

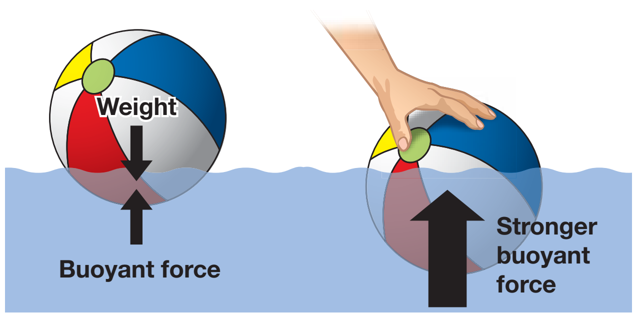
Weight and mass are not the same

We all tend to use the terms *weight* and *mass* interchangeably. In science however, *weight and mass are not the same thing*. Mass is a fundamental property of matter. **Weight** is a force, like any other pushing or pulling force, and is caused by Earth's gravity. It is easy to confuse mass and weight because heavy objects (more weight) have lots of mass and light objects (less weight) have little mass.

Buoyancy is a force

It is much easier to lift yourself in a swimming pool than to lift yourself on land. That is because the water in the pool exerts an upward force on you that acts in a direction opposite to your weight (Figure 4.13). We call this force **buoyancy**. Buoyancy is a measure of the upward force a fluid exerts on an object that is submerged.

Pushing a ball underwater



The strength of the buoyant force on an object in water depends on the volume of the object that is underwater. Suppose you have a large beach ball you want to submerge in a pool. As you keep pushing downward on the ball, you notice the buoyant force getting stronger and stronger. The greater the part of the ball you manage to push underwater, the stronger the force trying to push it back up. The strength of the buoyant force is proportional to the volume of the part of the ball that is submerged.

VOCABULARY

weight - the downward force of gravity acting on mass.

buoyancy - the measure of the upward force a fluid exerts on an object that is submerged.

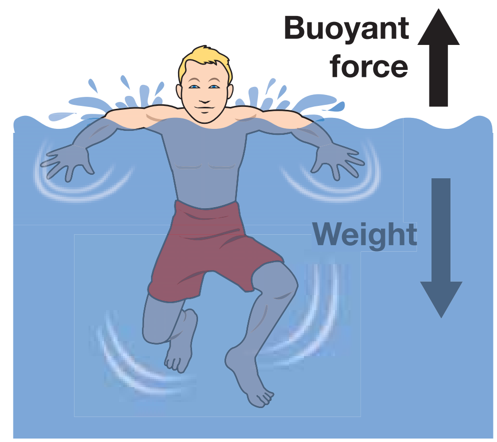
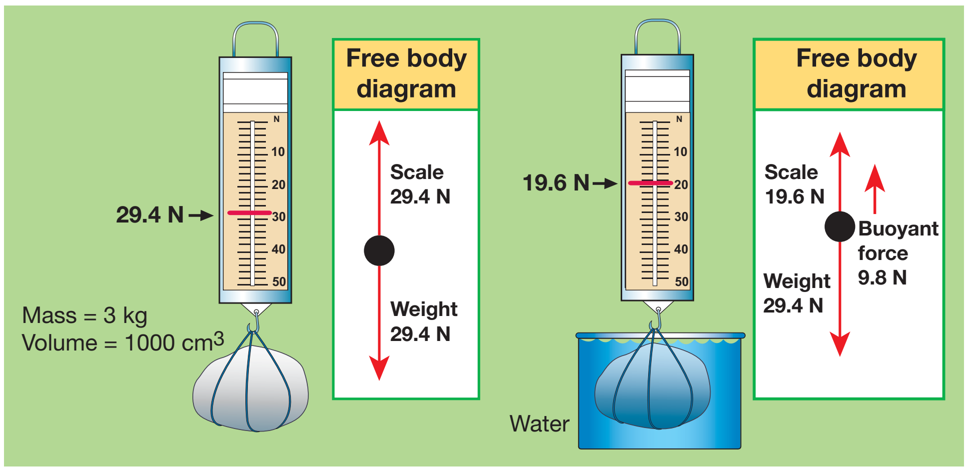


Figure 4.13: *The water in the pool exerts an upward force on your body, so the net force on you is lessened.*

Archimedes' principle

Archimedes' principle

In the third century BC, a Greek mathematician named Archimedes realized that buoyant force is equal to the weight of fluid displaced by an object. We call this relationship **Archimedes' principle**. For example, suppose a rock with a volume of 1,000 cubic centimeters is dropped into water (Figure 4.14). The rock displaces 1,000 cm^3 of water, which has a mass of 1 kilogram. The buoyant force on the rock is the weight of 1 kilogram of water, which is 9.8 newtons.



A simple buoyancy experiment

A simple experiment can be done to measure the buoyant force on a rock (or any object) with a spring scale. Suppose you have a rock with a volume of 1,000 cubic centimeters and a mass of three kilograms. In air, the scale shows the rock's weight as 29.4 newtons. The rock is then gradually immersed in water, but not allowed to touch the bottom or sides of the container. As the rock enters the water, the reading on the scale decreases. When the rock is completely submerged, the scale reads 19.6 newtons.

Calculating the buoyant force

Subtracting the two scale readings, 29.4 newtons and 19.6 newtons, results in a difference of 9.8 newtons. This is the buoyant force exerted on the rock, and it is the same as the weight of the 1,000 cubic centimeters of water the rock displaced.

VOCABULARY

Archimedes' principle - states that the buoyant force is equal to the weight of the fluid displaced by an object.

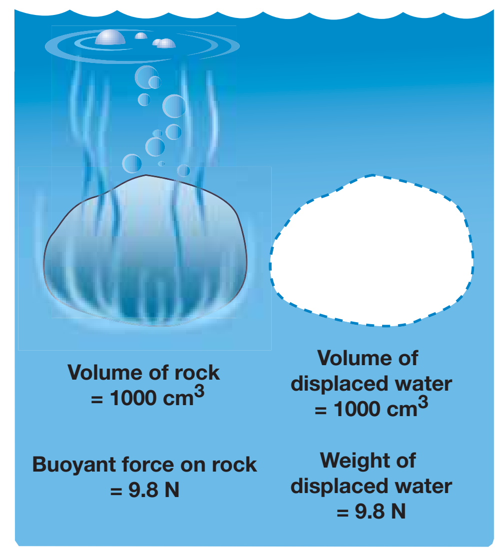


Figure 4.14: *A rock with a volume of 1,000 cm^3 experiences a buoyant force of 9.8 newtons.*

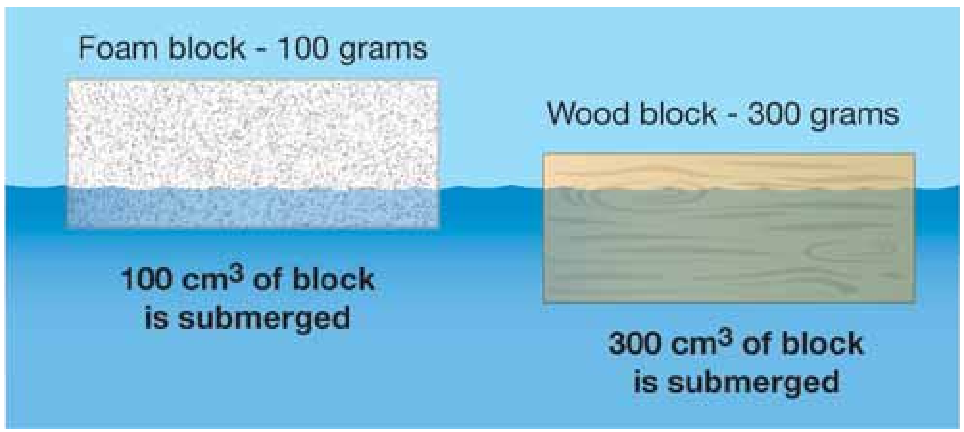
Sinking and floating

Comparing buoyant force and weight

Buoyancy explains why some objects sink and others float. A submerged object floats to the surface if the buoyant force is greater than its weight (Figure 4.15). If the buoyant force is less than its weight, then the object sinks.

Equilibrium

Suppose you place a block of foam in a tub of water. The block sinks partially below the surface. Then it floats without sinking any farther. The upward buoyant force perfectly balances the downward force of gravity (the block's weight). But how does the buoyant force "know" how strong to be to balance the weight?



Denser objects float lower in the water

You can see the answer to this question in the pictures above. If a foam block and a wood block of the same size are both floating, the wood block sinks farther into the water. Wood has a greater density, so the wood block weighs more. A greater buoyant force is needed to balance the wood block's weight, *so the wood block displaces more water*. The foam block has to sink only slightly to displace water with a weight equal to the block's weight. A floating object displaces just enough water to make the buoyant force equal to the object's weight.

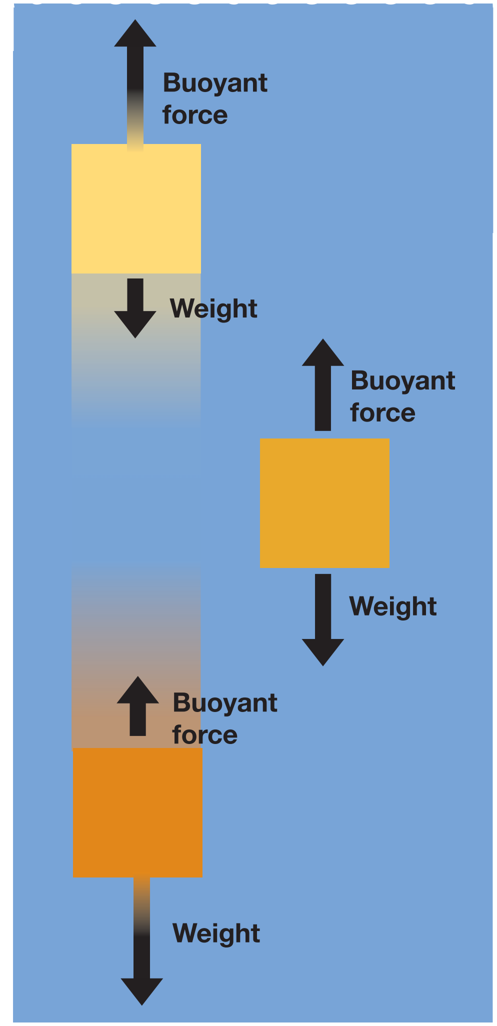


Figure 4.15: *Whether an object sinks or floats depends on how the buoyant force compares with the weight.*

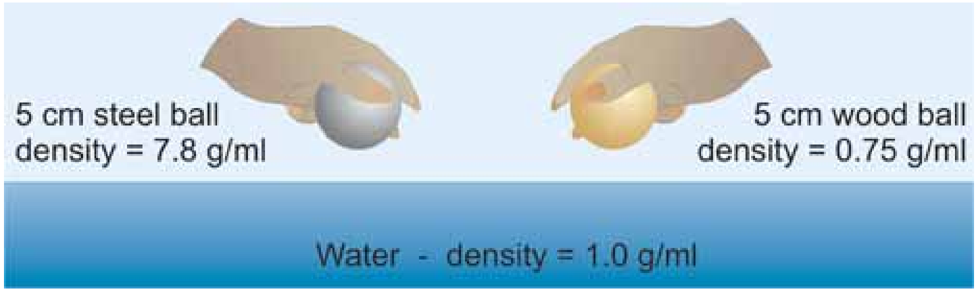
Density and buoyancy

Comparing densities

If you know an object's density, you can immediately predict whether it will sink or float — without measuring its weight. An object sinks if its density is greater than that of the liquid. It floats if its density is less than that of the liquid.

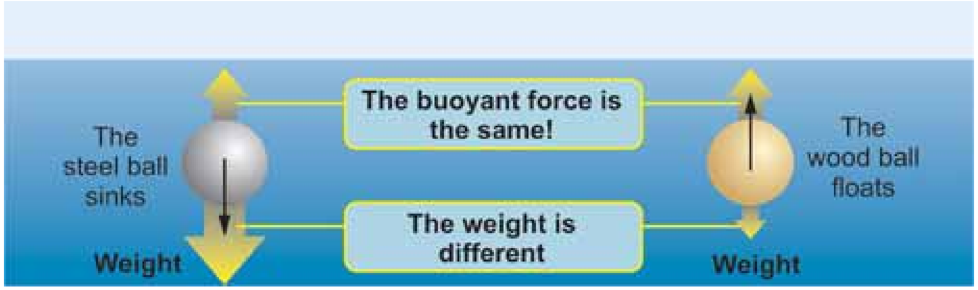
Two balls with the same volume but different density

To see why, picture dropping two balls in a pool of water. The balls have the same size and volume but have different densities. The steel ball has a density of 7.8 g/ml which is greater than the density of water (1.0 g/ml). The wood ball has a density of 0.75 g/ml, which is less than the density of water.



Why one sinks and the other floats

When they are completely underwater, both balls have the same buoyant force because they displace the same volume of water. However, the steel ball has more weight since it has a higher density. The steel ball sinks because steel's higher density makes the ball heavier than the same volume of water. The wood ball floats because wood's lower density makes the wood ball lighter than the same volume of displaced water.



An object with an average density GREATER than the density of water will sink

An object with an average density LESS than the density of water will float.

Average density

Average density is the total mass divided by the total volume.

Figure 4.16: *The meaning of average density.*

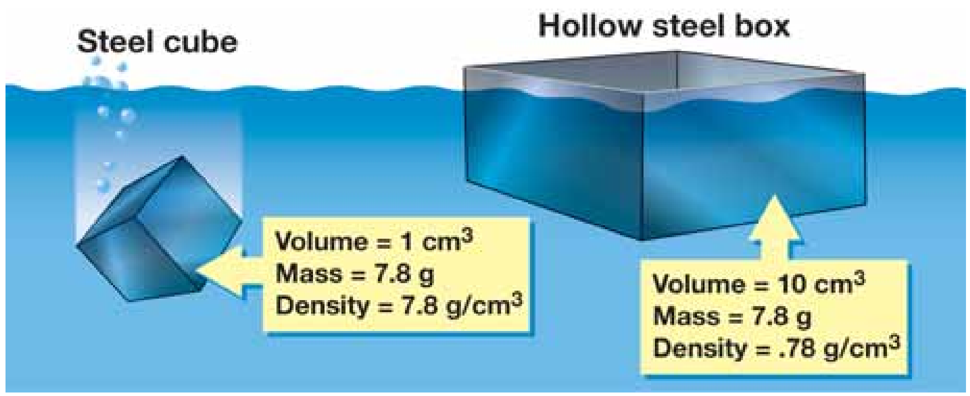
Boats and average density

How do steel boats float?

If you place a solid chunk of steel in water, it immediately sinks because the density of steel (7.8 g/cm^3) is much greater than the density of water (1.0 g/cm^3). So how is it that thousands of huge ships made of steel are floating around the world? The answer is that it is the *average density* that determines whether the object sinks or floats.

Solid steel sinks because it is denser than water

To make steel float, you have to reduce the *average* density somehow. Making the steel hollow does exactly that. Making a boat hollow expands its volume a tremendous amount without changing its mass. Steel is so strong that it is quite easy to reduce the average density of a boat to 10 percent of the density of water by making the shell of the boat relatively thin.



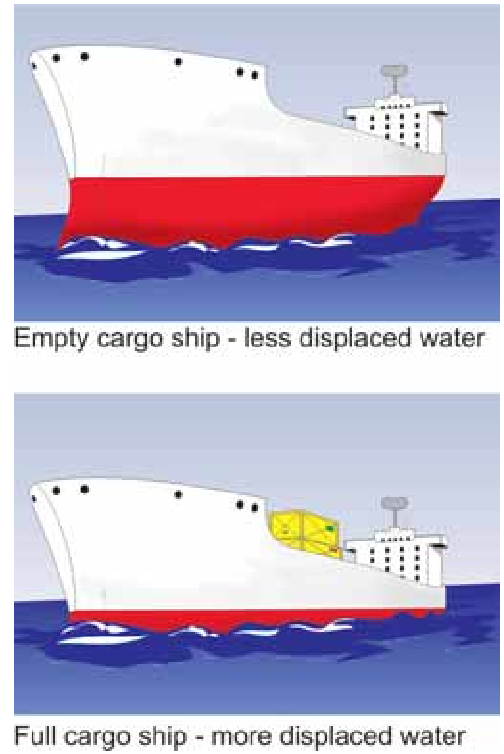


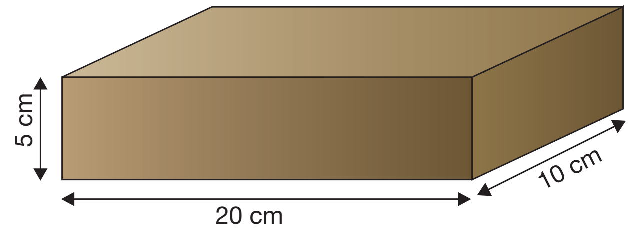
Figure 4.17: *A full ship has more mass than an empty ship. This means a full ship must displace more water (sink deeper) to make the buoyant force large enough to balance the ship's weight.*

Increasing volume decreases density

Ah, you say, but that is an empty ship. True, so the density of a new ship must be designed to be under 1.0 g/cm^3 to allow for cargo. When objects are placed in a boat, of course its average density increases. The boat must sink deeper to displace more water and increase the buoyant force (Figure 4.17). If you have seen a loaded cargo ship, you might have noticed that it sat lower in the water than an unloaded ship nearby. In fact, the limit to how much a ship can carry is set by how low in the water the ship can get before rough seas cause waves to break over the side of the sip.

4.2 Section Review

1. The buoyant force on an object depends on the _______ of the object that is underwater.
2. What happens to the buoyant force on an object as it is lowered into water? Why?
3. The buoyant force on an object is equal to the weight of the water it ________________.
4. When the buoyant force on an object is greater than its weight, the object ___________.



5. A rectangular object is 10 centimeters long, 5 centimeters high, and 20 centimeters wide. Its mass is 800 grams.
   a. Calculate the object's volume in cubic centimeters.
   b. Calculate the object's density in g/cm^3.
   c. Will the object float or sink in water? Explain.
6. Solid iron has a density of 7.9 g/cm3. Liquid mercury has a density of 13.6 g/cm^3. Will iron float or sink in mercury? Explain.
7. Why is it incorrect to say that heavy objects sink in water?
8. Steel is denser than water and yet steel ships float. Explain.

CHALLENGE

Legend has it that Archimedes added to his fame by using the concepts of volume and density to figure out whether a goldsmith had cheated Hiero II, the king of Syracuse. The goldsmith had been given a piece of gold of a known weight to make the crown. Hiero suspected the goldsmith had kept some of the gold for himself and replaced it with an equal weight of another metal. Explain the steps you could follow to determine whether or not the crown was pure gold.

PHYSICS CONNECTION

Airships in the Sky

What do televised football, baseball, and auto racing all have in common? You might think of sports, dedicated fans, and athletes. While these similarities are true, one common feature is that blimps provide video coverage for each of these events. Large, oval shaped airships hover over stadiums providing aerial shots of the action. Television cameras attached to the blimp's underside take wide-angle pictures. In addition, blimps provide advertising for major corporations. You have probably seen one in a sports telecast.

Hot air balloons

Anything that flies is an aircraft. In fact, the hot air balloon was the first aircraft invented, dating back to the early 1700s almost 200 years before the Wright brothers tested their first successful powered airplane. A hot air balloon depends on buoyancy forces for lift. Air in the balloon is kept hot by a burner. Hot air has a lower density than cold air. As long as the air inside the balloon is significantly hotter than the air outside, the balloon floats.

The density of air decreases with altitude. A hot air balloon floats upward until its average density matches the average density of the surrounding air. To go up father, the balloon pilot makes the air hotter inside the balloon, decreasing the average density. To go down, the pilot releases some hot air, making the balloon smaller and decreasing its average density.

The problem with hot air balloons is how to steer! With a hot air balloon you can only control motion up or down. The only way to steer is to change your altitude in hopes that the wind will be blowing the way you want to go at *some* altitude. This is all right if you are ballooning for fun. However, the direction of the wind is not reliable enough to use hot air balloons for travel or for shipping.

Blimps

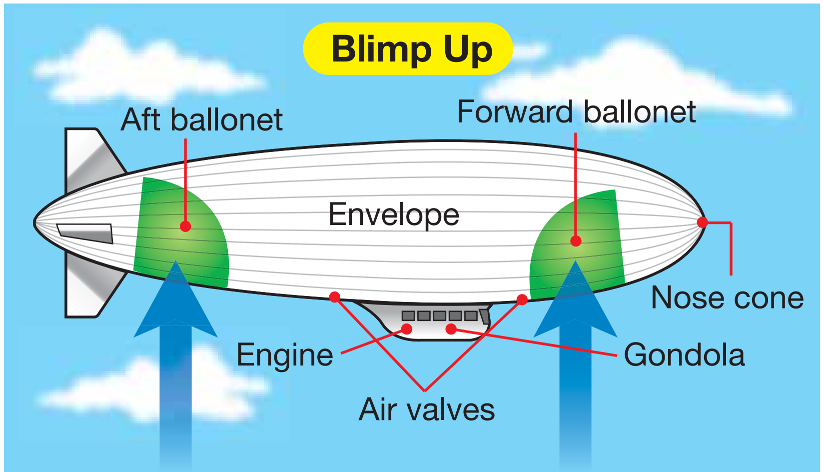
A blimp is a type of *airship*, like a hot air balloon. Like a hot air balloon, a blimp also gets its lift from buoyancy of surrounding air. However, a blimp is filled with helium, a gas that is lighter than air. Unlike a balloon, a blimp keeps its helium gas at the same temperature as the surrounding air.

A blimp has four major parts: the envelope, gondola, engines, and controls. The envelope is the large cavity filled with helium. Made of polyester fabric similar to spacesuits, the envelope is a cigar-shaped, aerodynamic design. The gondola carries passengers and pilots and contains the engines and controls. Gasoline powered engines move blimps an average of 35 miles per hour.

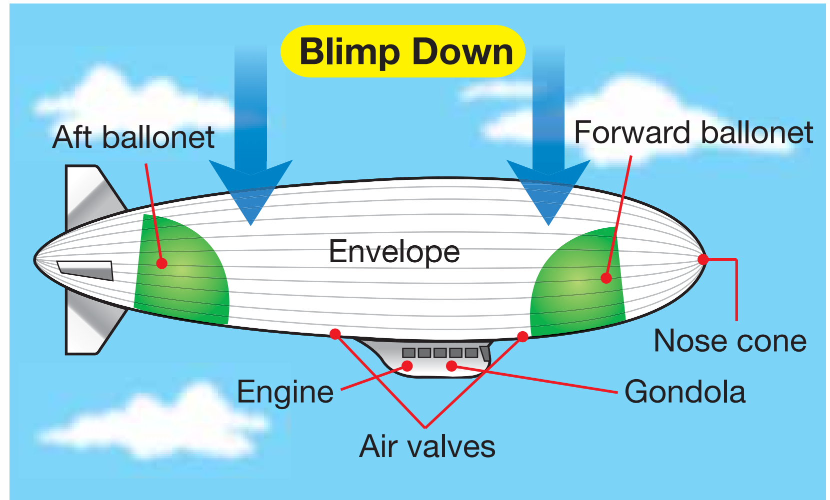
Because the blimp has a motor, it can steer with a rudder, like a boat. Controls allow the pilot to steer the blimp up, down, right, or left. This is a big advantage over a hot air balloon.

Henri Giffard invented the first powered airship in 1852. In 1900, Count Ferdinand von Zeppelin invented the first rigid airship with a metal structure providing its shape. For buoyancy, early blimps used hydrogen. Hydrogen is very light bit also very explosive! In fact, the famous Hindenburg blimp, filled with hydrogen, exploded and burned during an accident in New Jersey in 1937.

Today, blimps are filled with helium instead of hydrogen, and do not have a rigid steel structure. Instead, modern blimps are nothing more than a large, strong, gas balloons. The aerodynamic shape is maintained by keeping the pressure of the helium in the blimp greater than the pressure of the air outside, just like the balloons you get at a party.



1. Air is released from the ballonets through air vents controlled by air valves
2. Ballonets deflate causing the envelope to fill with **HELIUM**
3. Envelope air becomes lighter and less dense
4. Outside air becomes heavier and more dense
5. Positive buoyancy causes blimp to rise



1. Air fills ballonets through air vents controlled by air valves
2. Ballonets inflate causing the envelope to fill with **AIR**
3. Envelope air becomes heavier and denser
4. Outside air becomes lighter and less dense
5. Negative buoyancy causes blimp to descend

Controlling altitude in a blimp

Inside a blimp's envelope there are two compartments called ballonets. These are bags filled with relatively heavy air (not helium). The pilot controls the amount of air in the ballonets through air valves. Since air is heavier than helium, the pilot deflates or inflates the ballonets to make the blimp rise or fall. Changing the proportions of air and helium changes the blimp's average density. Just like a hot air balloon, the blimp rises or falls until its average density matches the surrounding air.

Blimps in science

Today blimps are used for more than just sporting events and advertising. The U.S. Geological Survey has used blimps to fly over volcanoes. A blimp is less likely to be damaged by ash than a helicopter or plane.

Blimps are also used to study whales and their behavior. One research blimp is outfitted with cameras and equipment for tracking whales. Picture taking is much more stable from a blimp than from an airplane. The stability allows cameras with high-power zoom lenses to take highly detailed pictures from far above the ocean surface.

Questions:

1. What is a blimp?
2. What is buoyancy and how does it affect a blimp
3. What are negative, positive, and neutral buoyancy, and how do they affect a blimp?