



Density and the Buoyant Force – Hot Air Balloon

What is air? We breathe it, we need it every minute of our lives, but what is it? We can't see it, smell it, or taste it. We don't even feel it like we can feel an object. Instead we only feel its force against us. It may seem like it doesn't exist, but air is actually made of many particles that are as real as those that are in a chair or table. They have mass and they take up space.

Air is also affected by gravity just like a chair or a table. You may not know it, but air is pulled toward the earth and stays close to the surface. The higher you fly into the sky, the less air you will pass through because gravity is pulling it down toward the ground.

So how do things fly? How can a hot air balloon fly upward when gravity is pulling it down? Something must be stronger than gravity. Something must be lifting the balloon into the air with more force than gravity is pulling down on it. This upward push, whether we see its effects in water or in air, is called the **buoyant** force. Buoyancy is a force that pushes objects upward against the pull of gravity. How strong this buoyant force is depends on two things: the density of the fluid (water or air, for example), and the density of the object we're studying (a helium balloon or a hot air balloon or a hollow plastic pool toy, for example). If the density of the object is less than the density of the fluid, there will be a net upward push by the fluid against the object, forcing it to move upwards.

The density of a material (this can be a solid, liquid, or gas) is simply the mass of the material divided by its volume. One milliliter of water weighs about one gram, so water has a density of one gram per milliliter. Anything with a density greater than that will sink in water, and anything with a density less than that will float. If you submerge such an item, it will rise back to the surface against the pull of gravity. At atmospheric pressure and room temperature, air has a density that is about 1/1000th that of water (0.001 g/mL). Anything with a density less than that will "float" in air, or be pushed upward by the more dense air that surrounds it. An object at the Earth's surface is essentially at the bottom of a giant container full of air. If it's released from the bottom of the container, it will rise until the density of the surrounding air is equal to its own density. We don't ordinarily see many things that have a density less than that of air, but helium balloons and hot air balloons are two of them. But how can a hot air balloon, which can easily carry 1000 pounds of passengers and equipment, have a density less than that of air?

The answer is in the hot air. When something is heated – regardless of whether it is a solid, liquid or gas – it will expand. If an object expands, that means it takes up more space, or has more volume, than it did before. Since it has the same mass but now has a greater volume, its density (mass/volume) decreases. The density of the hot air balloon is the mass of the entire balloon – this includes the nylon balloon material, the air within it, the gondola, the passengers, and the heating engine and fuel – divided by the volume of the entire thing. The density of the gondola and its contents is clearly greater than the density of air, but the density of the heated air inside the balloon is less than the density of the cooler surrounding air. The overall result is that when the air inside the balloon is heated to a high enough temperature, the entire balloon apparatus as a whole becomes less dense than the surrounding air, and buoyancy wins out over gravity. The balloon rises.

The air inside a hot air balloon expands when it is heated, but the balloon itself does not. If you've ever seen pictures of hot air balloons taking off, or even ridden in one yourself, you know that the balloon is already fully inflated when the hot air balloon is on the ground. The balloon itself doesn't expand as the balloon rises, because the hot air balloon has a hole in the bottom that allows heated air to escape. So when the air inside the balloon is heated, it expands and some of it escapes from the balloon. This means that the more you heat the air inside the balloon, the more it expands and the more escapes, leaving less mass of air inside the balloon. So the difference between a hot air balloon on the ground and one in the air is that the one in the air has a lower mass than the one on the ground, but they both have the same volume, and therefore the one with heated air has a lower density.

Here are some misconceptions about buoyancy.

1. Heat Rises: Not exactly. Heat is a form of energy, not a physical object that can rise or fall. Heating air causes it to spread out and become less dense. The warmer, less dense air rises because colder, denser air pushes it out of the way. Gravity continues to pull down on warm air, but the cold air pushes it up with more force than gravity pulls it down, causing it to rise.
2. Air doesn't have mass (or weight): Not true. We don't feel the weight of the air on top of us because the air particles are pushing up with the same pressure they're pushing down, so we don't feel it.
3. Weight determines if an object will sink or float: No, an object's density and the density of the fluid surrounding it determine if it will sink or float. Have you ever been on a cruise ship? It is very heavy, but it is still buoyant.
4. All objects with air inside them always float: No, density determines if an object will sink or float.

Activity: (You may need java installed on your computer. To install Java, go to <https://www.java.com/en/download/manual.jsp>.)

Take a hair dryer, face it up toward the ceiling and turn it on low. Now place a ping pong ball on top of the air going upward. What happens? The ping pong ball floats because air particles are pushing it upward.

Try the simulation:

1. Click on `Balloons-and-Buoyancy_en.jar`.
2. You will notice there is a pump on the right side. What happens when you pump the handle? Are there more or less molecules in the container? What happens to the temperature? Does it go up or down? Where are most of the molecules? Is gravity affecting the molecules?
3. Drag the scuba diver to the left to make the container bigger. Now that we are increasing the volume of the air outside of the balloon, what happens?
4. Add heat to the balloon. (The control is on the right side) What happens?
5. Now see if you can make changes that will blow the lid off the container. What changes worked? Can you separate heat from pressure?
6. Put 50 heavy pieces into the container. Add heat to the balloon and watch it move up and down. What do you notice about what is happening in the balloon? What type of energy is present in the balloon? It is kinetic and thermal. Thermal energy be transferred by convection, conduction and radiation. What type of transfer happens in our balloon? In our hot air balloon, convection is happening. Convection occurs when thermal energy is transferred through the movement of particles from one location to another. Further, the air moving in and out of the balloon forms convection currents. The heated air expands and is replaced by the cooler air. The cooler air is then heated and the process repeats again. Weather patterns are influenced by convection currents. Heating and cooling of homes is also an example of convection currents.
7. Would a hot air balloon work on the moon?
8. In the right bar, click on "Measurement Tools," then click on species information. Take a look at the average speed of the particles, then add heat under "Heat Control" below the chamber. How does the average speed change? How does the temperature change? How does the pressure change?
9. Click on "Layer Tool." Compare the pressure at the bottom and top of the chamber. Which is higher.
10. Adjust the gravity so that it is significantly higher. Describe what happens to the particles?
11. Explore different combinations.