

# Does air weigh anything?

A laboratory experiment from the  
Little Shop of Physics at  
Colorado State University



## Overview

Air is usually invisible, so most of us don't give it much thought at all. In fact, when students are asked about the mass or weight of air, many are perplexed. Air seems like it doesn't have mass, but it does. Since this is where atmospheric pressure comes from, it's an important concept to address.

## Theory

When you dive under the water, pressure increases; you can feel the increased pressure in your ears. The pressure comes from the weight of the water above you. Just as sea creatures travel through the water bodies of the world, land dwellers navigate through a sea of air.

You are, right now, about 100 kilometers deep in this sea called the atmosphere. All of the air above you has a significant weight! Imagine tracing out a square meter on the floor. If you measure the mass of the air above this area, up to the top of the atmosphere (more or less 100 kilometers up) you get a total mass of about 10,000 kg—about 10 tons! Even if you



*If you are careful, you can actually feel the difference between the weight of a “pumped” bottle and an “unpumped” one.*

## Necessary materials:

- One clean & dry 2-liter bottle
- One Fizzkeeper pump cap
- One triple beam balance

If you don't have a triple beam balance, you can use an equal arm balance and gram weights.

The Fizzkeeper pump cap is crucial to this experiment. These caps are designed to add air molecules to soda bottles to keep the carbonation under pressure so your soda stays fresh longer. You can obtain these pump caps at home stores such as Bed, Bath, & Beyond or you can order them directly from [www.jokari.com](http://www.jokari.com).

explain this to your students, some may still not believe that air has mass and weighs something. The experiment below will be quite surprising to those students, as they will experience putting extra air molecules into a bottle and measuring it directly!

We have seen experiments published in which students measure the mass of balloons before and after inflation. This doesn't work very well: the balloon changes size, and so the buoyant force on it changes. As the balloon displaces more air, it feels an upward force that negates the increased mass in the balloon. The experiment below uses a bottle, so the volume stays constant; the bottle expands very slightly when air is pumped in.

## Doing the Experiment

**SAFETY NOTE: A lot of pressure can build up in these bottles and the caps can become projectiles. When it's time for a student to release air from the bottle, be sure to have the student lay it on its side where it's not aimed at anyone, and slowly unscrew the cap.**

The experiment goes like this:

- Attach a Fizzkeeper cap to a 2-liter bottle but don't pump any extra air into the bottle. Have students feel the bottle, checking for weight and pressure.
- Weigh the bottle on a triple beam balance and record your findings.
- Ask your class to predict what will happen if you pump extra air molecules into the bottle and then measure its mass.
- Have students use the Fizzkeeper to pump more air molecules into the bottle. They can keep a count of the number of pumps if they like. In fact, if you have an accurate balance, students can measure the mass of the bottle as a function of the number of pumps. There is a clear trend, but at some point, the mass will stop increasing, as the pump caps won't pump any more air into the bottle.
- When the pumped bottle is pumped full as it can be, have the students feel the bottle, checking again for weight and pressure. What do they notice?
- Weigh the bottle on the triple balance beam and compare and discuss your two findings. If there are more molecules in the bottle, there's more pressure and more mass!

## Summing Up

This exercise is quick proof of the fact that air has mass. When you use the pump cap, more air molecules are pumped into the bottle. This increases the pressure, but it also increases the mass. You can easily increase the mass of the bottle by a few grams—a measurable amount!

## For More Information

CMMAP, the Center for Multi-Scale Modeling of Atmospheric Processes: <http://cmmmap.colostate.edu>

Little Shop of Physics: <http://littleshop.physics.colostate.edu>

# What causes pressure?

A laboratory experiment from the  
Little Shop of Physics at  
Colorado State University

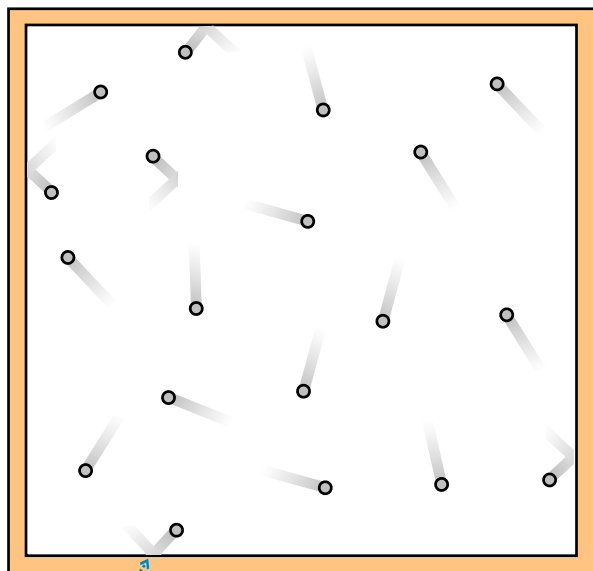


## Overview

In our everyday lives, we are exposed to many references to pressure: atmospheric conditions such as high pressure or low pressure, psychological conditions such as feeling under pressure, and medical conditions such as sinus pressure. All of these interpretations of pressure have a common element: a weight, a pushing, a force. But physicists have a very particular meaning for the word pressure. When you pump air into your bike tires, the air makes an outward force that keeps the tires firm. This force is due to the pressure of the air. But what causes this pressure?

## Theory

We can develop a pretty good understanding of pressure by thinking about an atomic-scale picture of what is going on in a gas. The molecules of a gas like air behave in a very simple manner: they move (at quite high speeds) in a straight line until they bump into something, then they bounce off and move in another direction. That's it!



The collisions of the particles with the walls of the container cause a force on the walls.

## Necessary materials:

- one long rope
- a large open area in the classroom or outside

We call this experiment “Molecules in a Box.” The students are the molecules, and the box is an area defined by the rope.

You can also do this experiment without a rope by defining a certain location as your box. Perhaps you have a tiled area that would work or a corner of your classroom. You can even define an imaginary box.

If the gas is in a container—a box—the molecules hit the sides of the box from time to time. These collisions with the walls make a force on the walls of the container; we call this the pressure of the gas. The pressure is defined as the total force on one wall divided by the area of the wall. But you can get a qualitative understanding of the pressure by thinking about the collisions: Lots of collisions means lots of pressure.

The pressure in a container of a gas depends on the number of molecules in the container, the volume, and the temperature. Physicists use the formula:

$$p = NkT/V$$

where  $p$  stands for pressure,  $N$  for the number of atoms,  $T$  for temperature (in Kelvin), and  $V$  for vol-

ume.  $k$  is a constant known as Boltzmann's constant.

What the equation really says is this:

- More molecules means more pressure.
- Higher temperature (meaning faster molecules!) means more pressure.
- A smaller container means more pressure.

All of these make sense given our atomic-scale picture of a gas. More molecules means more collisions; higher temperature means faster molecules that hit the walls more often (and harder!) and a smaller container means the molecules hit the sides more often as well.

Rather than diving right into the equation, do a conceptual warmup first: Show students what the equation means. And you can do this in a very kinesthetic manner by having them be the molecules...

## Doing the Experiment

Explain to your class that they will be taking part in a kinesthetic activity to demonstrate pressure, and some of them will be acting as air molecules in a container. Depending on the age and knowledge of the group, ask for a volunteer to answer the question: What is a molecule? If the student has difficulty with this, give an explanation that is appropriate for your group.

Call up four volunteers to hold the rope taut to make a square. Explain to the group that you are going to pretend that the rope forms the walls of a box. Have other students step inside the box and spread out facing any direction they choose. Tell them that they are going to act out the part of air molecules. Demonstrate or direct them to walk forward in the box. If they bump into each other or a wall of the box, they should bounce away and walk in their new straight path until they bump into something again. Explain that when they bump into the walls of the box and are forced to bounce back into the box, this is pressure.

Try several scenarios. Tell them that you are adding heat to the box and ask them how they should move. (Faster!) Have them act this out. Now suppose that heat is removed from the box and they've become cold molecules. How do they move now? (Slower!) Add or subtract molecules from the box. Reduce the volume of the box by shortening the rope and have the molecules continue to move around in the area. On each case, keep track of the frequency of collisions.

How do you "measure" the pressure? The quick way is to have students "beep" with gusto every time they bump into the rope. This will allow them to hear the difference between low pressure and high pressure: Lots of beeps means high pressure. But you can also get numbers: Run each situation for only 15 seconds. Have each person holding a corner of the box be in charge of one of the four walls of the box, keeping track of how many times the wall was bumped by individual molecules. Add the four sides up each time and compare the results of cold versus hot, smaller versus larger volume, and less versus more molecules. You can clearly show all of the variations noted above.

## Summing Up

This is a great way to introduce the concept of air pressure and illustrate how it varies with density and temperature. Once students have done this, they will be able to visualize more readily what is happening both vertically and horizontally in the atmosphere due to changes in pressure.

## For More Information

CMMAP, the Center for Multi-Scale Modeling of Atmospheric Processes: <http://cmmmap.colostate.edu>

Little Shop of Physics: <http://littleshop.physics.colostate.edu>

# Marshmallow Mashers

*In this activity, students will observe the effect of air pressure on marshmallows, and then can dine on this delicious experiment.*



## Grade Level

- 4th - 8th

## Science Focus

- air molecules
- air pressure

## Time Required

- 20-30 minutes

**Supplies** *Since mini marshmallows are not provided with this kit, this same activity may also be done with the ten pre-filled bottles of styrofoam packing peanuts included with the kit.*

Per Cooperative Group

*Enough supplies for ten cooperative groups of three*

- 1 empty 16 oz. plastic pop bottle, clean and dry
- a container of mini marshmallows to fill up half the bottle
- 1 pump cap (Fizzkeeper or any other brand)
- student activity-sheet Make A Marshmallow Masher

Per Class

- a chart pad (optional)
- markers (optional)

**Important Safety Note** *A lot of pressure can build up in these bottles and the caps can become projectiles. When it's time for students to release air from the bottles, be sure to have them lay their bottle on its side and slowly unscrew the cap on the bottle. You may want to collect the bottles when they are done experimenting so that students aren't pumping in air throughout the entire class period.*

## Doing the Activity

- Tell the class that you have an activity that will help them see the effects of air pressure. Show them the supplies that they will be using for the experiment: a clean and dry plastic pop bottle, a container of mini-marshmallows, the pump cap, and the student activity-sheet, Make A Marshmallow Masher. Explain that they will get to eat the marshmallows when they've finished the whole experiment. Pass out the student activity sheets and have students put their names and the date at the top.
- Ask students what are the two main ingredients in marshmallows. (sugar and air, a sugar foam concoction) Tell them that their first job is to put the marshmallows inside

the bottle. Have student helpers give a bottle and a container of marshmallows to each cooperative group.

- Tell them their next job is to put the special push cap on the bottle, but not to pump it yet. Ask them to squeeze the bottle and describe how it feels. Then ask them what they think will happen if they pump a lot of air molecules into the bottle. Using the space under question number 1, have them draw and/or write what they think will happen.
- Then follow direction number 2 on the Make A Marshmallow Masher student activity sheet and continue this procedure until you've completed the experiment.
- Have the helpers collect the pump caps and bottles while the students munch on the marshmallows.

### **Active Questioning, Explanation, and Discussion**

1. What did this experiment teach you about air pressure? (When you add more air molecules inside the bottle, the air pressure increases and compresses the marshmallows and the air inside them. When you unscrew the cap and the air pressure returns to normal, the marshmallows return to their original size.)
2. Can you think of other things we could put in the bottle that would demonstrate the effects of air pressure? (Foam, shaving cream, packing peanuts, candy Peeps, etc.)
3. What are some things that wouldn't compress inside the bottle? (Open-ended)

### **Other Experiment Extensions**

#### **Experiment Extension 1 – Balloon in a Bottle – (Teacher Demo)**

##### **Supplies**

Per Student

None

Per Class

1 clean and dry pop bottle with a hole in the bottom

1 balloon - long and skinny

a permanent marker

##### **Doing the Activity**

- Explain to students that you will be doing a demonstration to show them the effects of air pressure on a balloon in a bottle. Drop the balloon down through the opening of the bottle and stretch the open end of the balloon over the neck of the bottle. Ask students to predict what will happen to the balloon if you try to blow it up. Demonstrate and have a volunteer mark where the balloon reached to in the bottle. Discuss.
- Now ask students what they think will happen if the hole at the bottom of the bottle is covered and you try to blow up the balloon. Demonstrate and mark the reach of the balloon. Discuss why the balloon couldn't be blown up as far. (Once the balloon and the edge of the bottle make a seal, the air pressure below the balloon can't escape because the hole is blocked. This air pressure pushes back on the balloon and doesn't let you blow the balloon up very far.)
- Ask what would happen to the balloon if you lowered the air pressure in the bottom of

the bottle by taking some of the air out. Demonstrate by putting your mouth over the hole in the bottle and inhaling or show the video segment dealing with this from the Everyday Science: Pressure video. The balloon should spread out inside the bottle. Discuss. (By inhaling the air in the lower part of the bottle, a low pressure system is created. The higher pressure air in the balloon pushes further into the bottle and takes up the space.)

### **Experiment Extension 2 – Cloud in a Bottle**

#### **Supplies**

Per Cooperative Group

1 clean, empty plastic pop bottle

a tiny amount of isopropyl alcohol or water for each bottle

1 Fizzkeeper pump cap

Per Class

None

#### **Doing the Activity**

- Discuss what a cloud is with students. (Fog - Water vapor condenses into small droplets of liquid water in colder temperatures.)
- Tell them that they are going to make a cloud in a bottle. They need to put a small amount of isopropyl alcohol or water in their bottles and then add more air molecules by using the pump cap. They may need to set these aside for a time before they observe the cloud formation.
- Have students untwist the caps quickly, but carefully, and observe what they see, and also how the air feels as it comes out of the bottle. How did it feel and why? Discuss how they think this occurred.

Name \_\_\_\_\_ Date \_\_\_\_\_



## Make A Marshmallow Masher

*In this delicious experiment, you will make some discoveries about air pressure and marshmallows.*

You will need:

- 1 empty pop bottle, clean and dry
- A bunch of mini marshmallows
- 1 pump cap

1. Fill your bottle half full with the mini marshmallows. Put the special pump cap on the bottle. Squeeze the bottle. How do it feel? Draw a picture and/or write what you think will happen when you pump air into the bottle.
  
2. Now pump the cap as much as you can. Squeeze the bottle. How does it feel now? What happened to the marshmallows? Draw and/or write about how the marshmallows changed.
  
3. Shake the bottle. How do the marshmallows sound? Why do you think the marshmallows got smaller?
  
4. What do you think will happen when you take the cap off the bottle?
  
5. Watch the marshmallows as you slowly unscrew the cap on the bottle. What happened to them?
  
6. Why do you think this happened?



# Peep Poofer

*In this activity, students will observe the effect of air pressure on marshmallows, and then can dine on this delicious demonstration.*



## Grade Level

- 4th - 8th

## Science Focus

- air molecules
- air pressure

## Time Required

- 10 minutes

## Supplies

*This activity is designed as a Teacher demonstration. It can be done with Peeps (the marshmallow figures that appear at Easter and other holidays) but regular marshmallows will work, as will packing peanuts. But Peeps are a lot more fun.*

### Per Class

1 vacuum container & pump

Enough Peeps, marshmallows or packing peanuts to half fill the container

## Doing the Activity

- This demonstration makes a great follow-up to the Marshmallow Masher experiment. Students will have done some thinking about what causes pressure, and what effect pressure has on gases. And this is a great way to repeat these lessons in a different context.
- Explain to your students what the vacuum container does. It has a tight fitting lid, with a valve on top. The pump pulls air out of the container, and the valve keeps the air from coming back in until it is released.
- First, begin with an empty container. Show that the lid to the container has no screw threads or clips to hold it in place. It is loose! Next, pump several times to remove a good deal of air from the container. Now, ask a student to try to remove the lid. They won't be able to—until you release the valve to let air back into the container, in which case the lid is easily removed. Ask the students what was holding the lid in place, and why.
- Next, ask students to predict: when you add some Peeps to the container and pump out some air, what will happen? Do this, and see if their prediction was correct. Ask them to explain in some detail just what is going on.
- It is interesting to let the Peeps stay under vacuum for a while. How do they change?

## Active Questioning, Explanation, and Discussion

1. Why is the lid of the container so hard to remove when air is pumped from it? (There is less pressure inside, and this pressure difference results in a large force that presses the lid down.)
2. Why do the Peeps expand when the air is pumped from the container? (Pumping air molecules from the container reduces the pressure. The air inside the Peeps stays inside. When the pressure on the Peeps goes down, this air will expand—making the Peeps poof.)
3. Can you think of other things we could put in the container that would make an interesting effect? (Foam, shaving cream, packing peanuts, etc.)
4. This container is marketed as something to keep food fresh. Why might this be? (For one thing, it makes a very tight seal, as we have seen. A sealed container keeps flavors in. Another thing that can compromise freshness of certain foods like crackers and chips is moisture: they absorb moisture from the air, and this makes them seem less fresh as they are less crunchy. Pumping out air means pumping out oxygen and nitrogen—but it also means pumping out water vapor, so less moisture is absorbed. And pumping out oxygen means less oxidation, which also makes food taste less fresh.)

# If hot air rises, why is it cold in the mountains?

A laboratory experiment from the  
Little Shop of Physics at  
Colorado State University



## Overview

If you warm the air inside a balloon, the balloon will rise. But the temperature profile of the atmosphere shows that, near the earth, the air temperature drops as we go to higher elevations. Why doesn't the hot air end up at these higher elevations?

## Theory

Here is the simple answer to the question of the previous paragraph: It does.

When a parcel of air warms up near the surface of the earth, it *will* rise. But as it rises, it moves into regions of lower pressure. The pressure of the atmosphere drops with altitude, by about 10 kPa (100 millibar) per 1000 m.

As a rising parcel of air moves into regions of lower pressure, it expands. And as it expands, it cools. The air has to do work to expand, and so its temperature must decrease—the only possible source of energy for the work of the expansion is the thermal energy of the gas. For the large air masses that move in the atmosphere, this is an **adiabatic expansion**—no thermal energy is transferred from adjacent air.



Watching the temperature change as the air expands.

## Necessary materials:

- Two liter bottle
- Tire valve to fit in cap of bottle (Ace Hardware)
- Bike pump with pressure gauge
- LCD aquarium thermometer (Petco)

The most crucial piece is the tire valve. We found metal tire valves that can fit inside the cap of a two liter bottle. Having a bike pump with a gauge is also crucial; with the pump's gauge, we can inflate the bottle to a known pressure.

You can show that a rising parcel of dry air will cool by about 10°C for each 1000 m that it rises. This is the *dry adiabatic lapse rate*. A parcel of hot air will rise—but it cools as it does so. The air temperature will still be lower at higher elevations.

A measurement of the actual change in temperature with height in the atmosphere is the *environmental lapse rate*. This can vary, but a typical value, for the “standard atmosphere” is 6.5°C of cooling for a 1000 m rise in elevation. You can see that this is less than the cooling a rising parcel of air will experience. So a parcel of hot air will rise to a cer-

tain point, and then stop. When you heat up a hot air balloon, it becomes buoyant, but, as it rises, it cools, and so it only rises so far—unless you add more heat.

The case of a hot air balloon makes a nice energy transformation problem because you are exchanging thermal energy of the gas in the balloon for potential energy of the balloon and its cargo. The hot air balloon is, in some sense, a heat engine!

The actual atmosphere is more complicated, because moisture plays a role. As the air cools, water vapor can condense, giving up latent heat. This is something we will deal with in another experiment. For now, it's time to get to work!

## Doing the Experiment

This is a pretty straightforward experiment. You can get numbers from your instruments, but it's hard to do anything too significant with them because the expansion isn't adiabatic and isn't reversible. But you get a dramatic temperature change, which is easy to show.

**SAFETY NOTE I: The bottles will easily hold more pressure than the pump can provide as long as they are intact. If a bottle has a defect, though, it may not hold. If a bottle has any defect, replace it.**

**SAFETY NOTE II: When you pump the bottles up, they won't explode, but the caps can fly off at high speed if they are released. You should fasten the caps in place to eliminate this possibility. This isn't a big deal—folks open soda bottles all the time with no ill effects. But these bottle caps have valves in them so a bit of caution is warranted.**

The experiment goes like this:

- Pump up the bottle to a fixed pressure—about 2 bar is plenty. The air in the bottle will warm as you do this. Students can easily feel where the energy comes from for this increase in thermal energy!
- Let the bottle cool to room temperature.
- Let the air out of the valve, and notice the resulting cooling.

It's this last bit that is the crucial piece: As the air moves to lower pressure, it cools. Dramatically. A question to ask your students:

**Where does the thermal energy go as the air in the bottle cools?**

The work done in the expansion isn't as obvious as the work done in compressing the gas, but it is no less real! The air must push back the atmosphere as it escapes, and the energy to do this must come from somewhere—the thermal energy of the air in the bottle.

## Summing Up

This experiment is largely qualitative, but it does make a key point about energy transformations in air, one with good connections to the science of the atmosphere.

A final thought: Here's another way to think about the cooling with altitude: Thermal energy of a gas is due to the motion of the gas molecules. Suppose you aimed a particle straight up. It would rise, losing kinetic energy as it did so. So a parcel of such molecules would cool as it rose, as the speed of the molecules decreased!

## For More Information

CMMAP, the Center for Multi-Scale Modeling of Atmospheric Processes: <http://cmmmap.colostate.edu>

Little Shop of Physics: <http://littleshop.physics.colostate.edu>

# How can gravity make something go up?

A laboratory experiment from the Little Shop of Physics at Colorado State University



## Overview

If you warm the air in a balloon, it will rise. But why?

## Theory

When you warm up air, the molecules move faster. If they can, they will also move farther apart—reducing the density.

One cubic meter of air in Colorado has a mass of about 1.0 kg; if you warm air up by 30°C (not so hard to do) one cubic meter will only have a mass of 0.9 kg.

The balloon that you will build has a volume of about a cubic meter. So, when cold, the air in the balloon has a mass of 1.0 kg. Now,

suppose you put the balloon in the sun. It will heat up. The molecules will move faster, and some will escape. The balloon will have the same size, but the air inside will only have a mass of about 0.9 kg.

Now, here's the cool part: The balloon itself has a mass of less than 0.1 kg. So the mass of the balloon plus the air inside it is less than the mass of one cubic meter of air.

Because the balloon is where it is, there's one cubic meter of air, which has a mass of 1.0 kg, that has to be someplace else. This is what we call *displacement*.

If you were to raise the hot air balloon up, a larger mass of air could fall down to take its place. Suppose you had a pulley and a rope with a large mass on one end and a small mass on the other... If you let go of the rope, the large mass will fall and the small mass will rise.

The same thing happens here. Gravity will pull the denser, cooler air down, causing the warmer, less dense air (and the balloon containing it!) to rise!

## Necessary materials:

- Cheap, thin (.5 mil, at most!) black plastic garbage bags
- Masking tape or transparent tape

The most important thing is to make the bag really, really light. So use cheap thin bags and the lightest strongest tape you can find!



*The 16-bag version of this balloon is bigger and liftier.*

## Doing the Experiment

### Step 1: Building it. (Adapted from wikiHow)

The key thing is to use the cheapest, thinnest, cheesiest black plastic garbage bags you can find. Your final balloon will have a vaguely tetrahedral shape; this is the easiest solar hot air balloon we have ever made. You could whip one up in 15 minutes.

It uses 4 black plastic bags. You can easily scale it up to the 16-bag version illustrated in the picture, but this is quite a bit trickier.

1. Remove 4 trash bags from the roll.
2. Cut off the sealed end (as close to the seal as possible).
3. Find the long edge of the folded bag that is folded several times over.
4. Insert the blade of a pair of scissors into one of the folds and cut all the way to the other end. You should be able to spread the bag open into a 3ft x 5ft sheet of plastic.
5. Repeat this procedure for all 4 bags.
6. Join 2 bags together with masking tape, along the long (5ft) side of the sheets.
7. You should have a 5x6ft sheet of plastic. Attach another bag to one of the 5ft sides, and then the last bag. You should have a long, 12x5ft sheet of plastic.
8. Join the two shorter (5ft) ends with the masking tape.
9. You will now have a flat tube that measures 6ft x 5ft.
10. Seal one of the open ends with masking tape. This is Seam A. There should be a seam at the center of the new seam.
11. At the other end of this seam, take the remaining open end and pull it open.
12. Seal this opening, so the seam is perpendicular to seam A.
13. Cut about 5 inches off of one of the corners, and invert the entire balloon like a sock.
14. When the balloon is inflated, it should be a tetrahedron, similar to a pyramid.

### Step 2: Flying it.

If you can, give yourself a head start by filling the balloon up with a hair dryer. If you do so, and you seal it off, it will rise and keep on rising. Tie it to a string or you'll need to make another...

## Summing Up

This experiment is a good one to illustrate what happens to air masses in the atmosphere: Warm ones rise, cool ones sink. Both happen here; the balloon is the one we see, but the falling cool air is the key. The pull of gravity on this denser air causes the less dense air to rise!

## For More Information

CMMAP, the Center for Multi-Scale Modeling of Atmospheric Processes: <http://cmmmap.colostate.edu>

Little Shop of Physics: <http://littleshop.physics.colostate.edu>

# Why do clouds tend to form in the afternoon?

A laboratory experiment from the Little Shop of Physics at Colorado State University



## Overview

In Colorado, the days usually dawn sunny and clear. But later in the day, clouds often form

You've seen this. And you likely know that clouds form when parcels of air are rising. Why does the air stay put until later in the day, and then start rising?

## Theory

Air rises for a simple reason: It warms up. And warm air rises. But there is more to the story.

When the sun rises, it warms the earth. So air near the earth's surface will warm. But it won't go anywhere just yet; we say that the air is *stable*.

Imagine that you did "nudge" a parcel of air, and move it upward. As this rising parcel of air moves upward, it expands. And as it expands, it cools. (The air has to do work to expand, and so its temperature must decrease—the only possible source of energy for the work of the expansion is the thermal energy of the gas. For the large air masses that move in the atmosphere, this is an adiabatic expansion—no thermal energy is transferred from adjacent air.)



How many cases can you stack? Anyone can do 6, but no one can do 10. Try it!

## Necessary materials:

- 2" PVC pipe cap
- CD cases (with CDs or not)

The pipe cap is the crucial piece; you can find these at any hardware store. You can use different sizes; they will just require more or fewer cases to make a transition to instability. A 2" cap needs 8 cases. Smaller caps need fewer, larger caps more.

A rising parcel of dry air will cool by about  $10^{\circ}\text{C}$  for each 1000 m that it rises. This is called the *dry adiabatic lapse rate*. So the parcel of air the we "nudged" upward will cool.

Now, suppose you measure how the temperature varies with altitude in the atmosphere. A measurement of the actual change in temperature with height in the atmosphere is the *environmental lapse rate*. This can vary, but a typical value, for the "standard atmosphere" is  $6.5^{\circ}\text{C}$  of cooling for a 1000 m rise in elevation.

This means that a parcel of air that we nudge upward will be cooler than the air it meets—it cools off by  $10^{\circ}\text{C}$  for every 1000 m it rises, but the air only cools off by  $6.5^{\circ}\text{C}$ . This means that the atmosphere will be sta-

ble. The parcel we nudged upward will cool off, be cooler than the air surrounding it, and then fall.

Now suppose you warm up the air near the earth so that the temperature falls more quickly with height. Suppose the temperature drops by  $12^{\circ}\text{C}$  for every 1000 m. Then the air parcel we nudge upward will cool less than the air around it. The air will be warmer than the air around it, so it will keep on rising. A small nudge turns into a runaway rise—the air is unstable!

As the day heats up, this is exactly what happens. The temperature profile changes until the atmosphere becomes unstable, and air masses start to rise, forming clouds as they go.

The actual story is a bit more complicated, but the key element is the transition from stable to unstable. And that's something we can demonstrate in a very nice way with a mechanical system. The end of a 2" PVC pipe cap (a plumbing part) is a section of a sphere with a 3" diameter. If you place a block (or a stack of CDs) that is less than 3" tall on the end of the cap, it is stable; a small nudge will just make it rock, but it will stay put. Anything more than 3" tall is unstable. No matter how hard you try, a stray vibration will cause it to tip, and it won't rock back. The small nudge will grow until it falls off. The transition from stable to unstable occurs at about 8 CDs. (The transition might not be at exactly 3" because the cases can flex a small amount.) Anyone can stack 6 CDs, but no one can stack 10. Try it and see!

## Doing the Experiment

Students enjoy this activity as they can have a friendly competition with friends to see who can stack the most CD cases on the cap. Of course, if they each do this carefully, they'll all tie! When they reach a certain number of cases, it is just impossible to stack any more. Here's how it goes:

- Place the PVC cap on a level surface with the rounded side up.
- Take one CD case and carefully balance it horizontally on the rounded top of the cap.
- Give the case a little push with your finger on one of the edges. It should rock a bit, but not fall. This means it's stable.
- Now, add a second CD case. Is it still stable?
- Try stacking more CD cases, giving the stack a nudge each time to test its stability.
- At some point it will be impossible to add any more cases—the stack will be unstable. At this point, any nudge, any little wiggle, will grow. You simply can't balance the stack, no matter how hard you try.
- Have students compare their results with others in the class.

After doing the experiment, discuss the transition between stable and unstable with your students.

## Summing Up

This experiment is largely qualitative, but it does make a key point about the transition between stable and unstable situations. There's a tipping point where the behavior changes. And we see the same thing in the atmosphere, which is why a clear day may suddenly give rise to the formation of towering stacks of cumulus clouds!

## For More Information

CMMAP, the Center for Multi-Scale Modeling of Atmospheric Processes: <http://cmmmap.colostate.edu>

Little Shop of Physics: <http://littleshop.physics.colostate.edu>