Why don’t clouds fall?

A cloud is made of tiny drops of liquid water. Water is about 800 times heavier than the same amount of air. So what is holding the cloud up?

Before you talk to anyone: write your own answer on the board under your name. One or two sentences is enough. Any answer is fine for now.

How tonight works

Your group will work through five short problems, one step at a time. When your group finishes a step, **ask for help or a check-in**. The person who comes over will choose **one person** from your group to explain your answer. If they can explain it, your group gets the next step. So before you ask, make sure *everyone* in your group understands.

Each person has a job. Switch jobs at every new step.

Writer	Holds the *only* marker. Writes only what the group agrees on. Keeps asking, “What should I write?”
Questioner	Questions every number. “Is that too big? Too small? How do we know?”
Checker	Checks the units at every step. Makes sure the quietest person gets heard.

For Step 1, the Writer should be the person who has taken the *least* physics. Pass the jobs to the left at each new step.

Three habits of physicists

1. **Estimate.** Round numbers to make the math easy: $\pi \approx 3$ and $9.8 \approx 10$. Getting close is the goal, not getting every digit.
2. **Check units.** If the units come out wrong, the answer is wrong.
3. **Compare.** A number only means something when you compare it to something you already know.

Stuck? Ask for a **hint card**. There are a few for every step.

STEP 1 OF 5

How heavy is a raindrop?

The idea

Density tells you how much mass fits in a certain volume: density = mass ÷ volume.
Water has a density of 1000 kg per cubic meter. A 1-liter water bottle holds 1 kg of water.
Weight is the pull of gravity on something: weight = mass × g.
Weight is a force, measured in newtons (N).

Your task

A typical raindrop is shaped like a ball (a sphere) with a radius of about 1 mm.

(a) About how big is its volume, in cubic meters?

(b) About how much mass does it have? Give your answer in kg *and* in milligrams (mg).

(c) What is its weight?

Numbers you may need

Density of water $= 1000\ \text{kg/m}^3$ $g = 9.8\ \text{m/s}^2$ Volume of a sphere $= \frac{4}{3}\pi r^3$
$1\ \text{mm} = 0.001\ \text{m} = 10^{-3}\ \text{m}$ $1\ \text{mg} = 10^{-6}\ \text{kg}$

Does your answer make sense?

About how many raindrops would it take to fill a 1-liter bottle? Does that number seem believable?

Extra challenge (only if your group finishes early)

The drops inside a cloud are much smaller than raindrops. Their radius is about 10 micrometers (10 μm). A micrometer is a millionth of a meter. A human hair is about 70 μm wide.

- How many cloud drops would have to join together to make one raindrop? Try it without a calculator.

STEP 2 OF 5

Falling with no air

The idea

If there were no air, everything would speed up at the same rate as it fell. After falling from rest through a height h, an object's speed is

$$v = \sqrt{2gh}.$$

If you know where this formula comes from, show it on the board. If not, just use it.

Your task

Rain clouds are often about 2 km above the ground.

(a) If there were no air, how fast would a raindrop be going when it hit the ground? Give your answer in meters per second (m/s) and in miles per hour (mph).

(b) Does it matter how heavy the drop is? Why or why not?

Numbers you may need

$g = 9.8\ \text{m/s}^2$ $h = 2\ \text{km} = 2000\ \text{m}$ $1\ \text{m/s} \approx 2.2\ \text{mph}$

Some speeds to compare: a car on the freeway ≈ 30 m/s a fast baseball pitch ≈ 45 m/s a jet taking off ≈ 75 m/s

Does your answer make sense?

Would you want to stand outside in rain like this? Real rain doesn't hurt. So something is missing from this picture. **What is it?** Write your group's answer on the board.

Extra challenge (only if your group finishes early)

- With no air, how many seconds would the fall take? (Use $h = \frac{1}{2}gt^2$.)
- A real raindrop takes about **5 minutes** to fall 2 km. What is its average speed? Save this number for Step 3.

STEP 3 OF 5

The air pushes back

The idea

When something falls through air, the air pushes back on it. This push is called **drag**. The faster the drop falls, the harder the air pushes. At some speed, the push from the air equals the drop's weight. Then the drop stops speeding up and falls at a steady speed. That steady speed is called the **terminal speed**.

A useful trick: let the units build the formula

Every quantity has units made from kilograms (kg), meters (m), and seconds (s). Often only one combination of the quantities has the units you need.
Example. How long does it take to fall a height h? You know h (in m) and g (in $\mathrm{m/s^2}$). The only way to get seconds is $\sqrt{h/g}$. For $h = 2000$ m, this gives about 14 s. The exact answer is 20 s. The trick gets you close, but it can't find plain numbers like 2 or π.

Your task

(a) As a group, list everything you think could change how hard the air pushes on a falling drop.

(b) Suppose the push depends on only three things: the density of air, the drop's speed v, and its radius r. Combine them to get something with the units of a force: $\mathrm{kg{\cdot}m/s^2}$.

(c) Set the air's push equal to the drop's weight. Solve for the speed v.

(d) Find v for a raindrop with $r = 1$ mm. You can leave out the $\frac{4}{3}\pi$ in the weight to keep things simple.

Numbers you may need

Density of air $= 1.2\ \mathrm{kg/m^3}$ Density of water $= 1000\ \mathrm{kg/m^3}$ $g = 9.8\ \mathrm{m/s^2}$ $r = 10^{-3}$ m

Does your answer make sense?

The **measured** speed of a raindrop this size is about 6.5 m/s. How close did you get? Compare with your answer from the Step 2 challenge, if you did it. If you're off by a factor of 2, is that good or bad?

Extra challenge (only if your group finishes early)

- Using your formula: if a drop's radius is 4 times bigger, how many times faster does it fall?
- Hailstones can be several centimeters across. Estimate how fast a hailstone with a 2 cm radius falls. (The density of ice is about $900\ \mathrm{kg/m^3}$.)

STEP 4 OF 5

When the formula fails

Your task

(a) Use your formula from Step 3 for a **cloud drop** with radius 10 μm. The **measured** speed of a cloud drop is about 1 cm/s (0.01 m/s). How close is your answer?

Something new: stickiness

When a formula gives the wrong answer, it's telling you something is missing. Here is one missing piece.
Fluids are a little bit sticky: each layer of fluid drags on the layers next to it. This stickiness is called **viscosity**, written η (the Greek letter "eta"). Honey is very sticky. Air is only slightly sticky. But for very small, slow things, air's stickiness matters more than its density.

(b) Now suppose the air's push depends on the stickiness of air η, the speed v, and the radius r, but *not* on the density of air. Combine them to make a force.

(c) Set this new push equal to the weight. Solve for the speed v.

(d) Find v for the cloud drop, $r = 10\ \mu$m. Compare with 1 cm/s.

Numbers you may need

Stickiness of air: $\eta = 1.8 \times 10^{-5}\ \text{kg}/(\text{m}\cdot\text{s})$ Density of water $= 1000\ \text{kg/m}^3$
$g = 9.8\ \text{m/s}^2$ $10\ \mu\text{m} = 10^{-5}\ \text{m}$

Does your answer make sense?

Try your *new* formula on the 1 mm raindrop. Compare the result with your Step 2 answer (no air at all). What went wrong?
You now have two formulas, and each one fails somewhere. When should you use which one?

Extra challenge (only if your group finishes early)

- At 1 cm/s, how many hours would a cloud drop take to fall 1 km?

STEP 5 OF 5

Which formula wins?

Your task

(a) Divide the air's push from Step 3 by the air's push from Step 4. Cancel everything you can. What units are left?

(b) Find the value of this ratio for the raindrop (use $v = 6.5$ m/s) and for the cloud drop (use $v = 0.01$ m/s).

(c) If the ratio is much bigger than 1, which formula should you trust? What if it is much smaller than 1?

(d) About how big does a drop have to be for the two formulas to give the same speed?

(e) **Now answer the opening question as a group: why don't clouds fall?**

Numbers you may need

The air inside a cloud is almost never still. Air often rises at speeds from about 10 cm/s to several m/s, and even faster in thunderstorms.

What you just found

Your ratio has a name: the **Reynolds number**. It tells you which kind of push from a fluid is more important, the one from its density or the one from its stickiness. For a swimming bacterium, the ratio is tiny, about 0.00001. To a bacterium, water feels thicker than honey feels to you. For a person swimming, the ratio is about 1,000,000. Same water, very different experience.

Extra challenge (only if your group finishes early)

- Air rising at 1 m/s can hold up drops below a certain size. About how big is that size?
- Below a cloud, the air is often drier, so falling drops start to evaporate. Which drops are more likely to reach the ground, big ones or small ones? Why?

WHOLE-ROOM DISCUSSION

Can we make it rain?

For decades, Utah has "seeded" clouds in winter to add snow to the mountains. The state has recently made the program bigger. Utah pays for it because it needs the water.

A cloud can hold a lot of water and still not produce any rain or snow.

1. Using what your group found tonight, explain how a cloud can hold lots of water without any of it falling.
2. What has to happen to the tiny cloud drops before rain or snow can reach the ground?
3. If you wanted to *make* a cloud produce rain or snow, what would you try to do to its drops?
4. How could you tell whether seeding a cloud actually worked? What would you measure, and what would you compare it to?