14

CHAPTER 14

Gases

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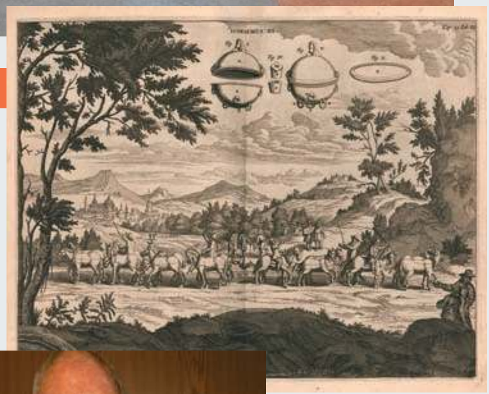

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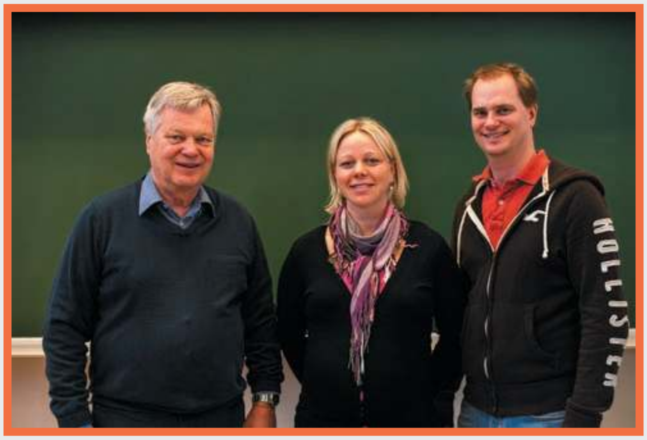
1 Forces due to atmospheric pressure are nicely shown by Swedish father-and-son physics professors, P. O. and Johan Zetterberg, who pull on a classroom model of the Magdeburg hemispheres. 2 A print of Otto von Guericke's famous 1654 demonstration of the original Magdeburg hemispheres, which when evacuated of air couldn't be pulled apart by two teams of horses. 3 With a spool and piece of card, Evan Jones plays with Bernoulli. When he blows through the hole in the spool and reduces the air pressure between the card and spool, the atmospheric pressure on the card's outside pushes it inward. (If you try this, punch a pin through the middle of the card for stability.) 4 Ole Anton Haugland, kneeling, encourages his Norwegian in-service physics teachers to build hot-air balloons from tissue paper.

Physics is firmly established in the educational mainstream in southern Sweden. Contributing to that has been the teaching effort of Per Olof Zetterberg at Lund University. Per Olof, known simply as P.O., contends that a student's first university course in physics should be a pleasurable experience. That's right, *pleasurable*. By being pleasurable, his course has inspired many students to major in physics who may not otherwise have. P.O. presents physics to beginning students as "fascination first; rigor later—when they are prepared." P.O. is joined by his son Johan, also a PhD physicist, a recent addition to the Lund University faculty. This father-and-son team, playfully pulling on the Magdeburg hemispheres as shown in the chapter-opener photo, are joined by Johan's fiancée, physicist Sara Blomberg, together making an impressive Lund team that elevates public appreciation of physics. The team further promotes this appreciation by presenting physics demonstrations enhanced by laser light activity to communities in and outside of Sweden. Their motto is "Have Physics, will travel!" With their dedication to physics education, helped by their good energy, the Lund team contributes to physics being alive and well in Scandinavia.



14.1 The Atmosphere

That's right. Ninety-nine percent of Earth's atmosphere is below an altitude of 30 km (only 0.5% of Earth's radius).

The thickness of our atmosphere is determined by two competing factors: the kinetic energy of its molecules, which tends to spread the molecules apart, and gravity, which tends to hold them near Earth. If Earth's gravity were somehow turned off, atmospheric molecules would dissipate and disappear. Or if gravity acted but the molecules moved too slowly to form a gas (as might occur on a remote, cold planet), our "atmosphere" would be a liquid or solid layer, just so much more matter lying on the ground. There would be nothing to breathe. The atmosphere keeps us alive and warm, and without it, we would perish within minutes.

But our atmosphere is a happy compromise between energetic molecules that tend to fly away and gravity that holds them back. Without solar energy, air molecules would lie on Earth's surface the way popcorn settles at the bottom of a popcorn popper. But, if heat is added to the popcorn and to the atmospheric gases, both bumble their way up to higher altitudes. Pieces of popcorn in a popper attain speeds of a few kilometers per hour and reach altitudes up to a meter or two; molecules in the air move at speeds of about 1600 kilometers per hour and bumble up to many kilometers in altitude. Fortunately, there is an energizing Sun, there is gravity, and Earth has an atmosphere.

The exact height of the atmosphere has no real meaning because the air gets progressively thinner and thinner the higher one travels upward. Eventually, it thins out to emptiness in interplanetary space. Even in the vacuous regions of interplanetary space, however, there is a gas density of about one molecule per cubic centimeter. This is primarily hydrogen, the most plentiful element in the universe. About 50% of the atmosphere is below an altitude of 5.6 km (18,000 ft), 75% is below 11 km

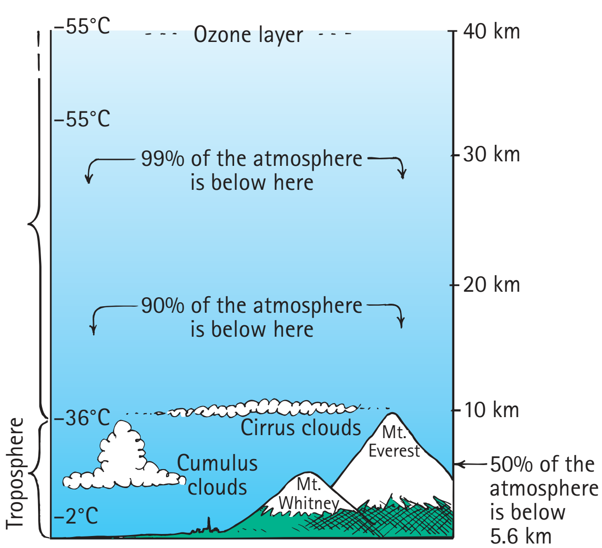


FIGURE 14.1
The atmosphere. Air is more compressed at sea level than at higher altitudes. Like feathers in a huge pile, what's at the bottom is more squashed than what's nearer the top.

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- Gases as well as liquids flow; hence, both are called *fluids*. A gas expands indefinitely and fills all the space available to it. Only when the quantity of gas is very large, such as in the atmosphere of a planet or a star, do gravitational forces limit the size or shape of a gas.

(36,000 ft), 90% is below 18 km (60,000 ft), and 99% is below about 30 km (100,000 ft) (Figure 14.1). A detailed description of the atmosphere can be found on various Web sites.

CHECK POINT

Why do your ears sometimes pop when you change altitude—say, moving in a skyscraper elevator or descending in an airplane?

CHECK YOUR ANSWER

A change in altitude means a change in air pressure, as discussed in the next section, and this causes a temporary imbalance in the pressures on the two sides of your eardrum.

14.2 Atmospheric Pressure

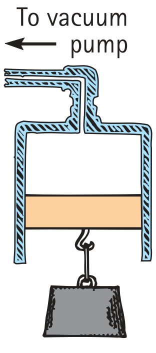

FIGURE 14.2
Is the piston that supports the load pulled up or pushed up?

We live at the bottom of an ocean of air. The atmosphere, much like the water in a lake, exerts pressure. For example, when the air pressure inside a cylinder like the one shown in Figure 14.2 is reduced, there is an upward force on the piston from the air outside. This force is great enough to lift a heavy weight. If the inside diameter of the cylinder is 10 cm or more, a person can be suspended by this force.

Contrary to common thought, what the experiment of Figure 14.2 does *not* show is a "force of suction." If we say there is a force of suction, then we assume that a vacuum can exert a force. But what is a vacuum? It is an absence of matter; it is a condition of nothingness. How can nothing exert a force? The piston holding the weight up in Figure 14.2 is not sucked upward. The piston is pushed by the weight of the atmosphere.

Just as water pressure is caused by the weight of water, **atmospheric pressure** is caused by the weight of air. We have adapted so completely to the invisible air that we don't feel it, and we sometimes forget that it has weight. Perhaps a fish "forgets" about the weight of water in the same way. The reason we don't feel this weight crushing against our bodies is that the pressure inside our bodies balances the pressure of the surrounding air. There is no net force for us to sense.

At sea level, 1 m^3 of air has a mass of about 1.25 kg. So the air in your kid sister's small bedroom weighs about as much as she does! The density of air decreases with altitude. At 10 km, for example, 1 m^3 of air has a mass of about 0.4 kg. To

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- Many deep-sea creatures experience enormous water pressures on their bodies, but they suffer no ill effects. As for us at the bottom of Earth's atmosphere, no net force or strain is exerted on them because the pressures inside their bodies match the surrounding fluid pressure. For many creatures, but not all, problems occur when they change depth too suddenly. Scuba divers, for example, who make the mistake of rising to the surface too quickly experience pain and possible death from rapid decompression—a condition known as the bends. (*Scuba* is an acronym for Self-Contained Underwater Breathing Apparatus.) Marine biologists are looking for ways to bring depth-sensitive deep-sea creatures to the surface without killing them.

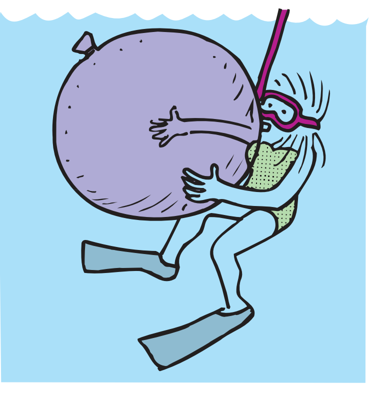

FIGURE 14.3
You don't notice the weight of a bag of water while you're submerged in water. Similarly, you aren't aware of the weight of air while you are submerged in an "ocean" of air.

compensate for this, airplanes are pressurized; the additional air needed to fully pressurize a modern jumbo jet, for example, is more than 1000 kg. Air is heavy if you have enough of it. If your kid sister doesn't believe that air has weight, you can show her why she falsely perceives the air to be weight-free. If you hand her a plastic bag of water, she'll tell you that it has weight. But, if you hand her the same bag of water while she's submerged in a swimming pool, she won't feel its weight. That's because she and the bag are surrounded by water. Likewise with the air that is all around us.

Consider the mass of air in an upright 30-km-tall bamboo pole that has an inside cross-sectional area of 1 cm^2. If the density of the air inside the pole matches the density of the air outside, the mass of enclosed air would be about 1 kg. The weight of this much air is about 10 N. So the air pressure at the bottom of the bamboo pole would be about 10 N per square centimeter (10 N/cm^2). Of course, the same is true without the bamboo pole. There are 10,000 cm^2 in 1 m^2, so a column of air 1 m^2 in cross-section that extends up through the atmosphere has a mass of about 10,000 kg. The weight of this air is about 100,000 N (10^5 N). This weight produces a pressure of 100,000 N/m^2—or, equivalently, 100,000 pascals or 100 kilopascals. To be more exact, the average atmospheric pressure at sea level is 101.3 kilopascals (101.3 kPa).[1]

The pressure of the atmosphere is not uniform. Besides altitude variations, atmospheric pressure varies from one locality to the next, and from day to day. This leads to moving weather fronts and storms that shape our weather. When a high-pressure system approaches, you can expect cooler temperatures and clear skies. When a low-pressure system approaches, expect warmer weather, rain, and storms. Measurement of changing air pressure is important to meteorologists when predicting the weather.

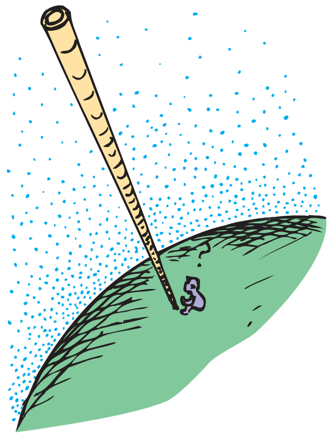

FIGURE 14.4
The mass of air that would occupy a bamboo pole that extends 30 km up—to the "top" of the atmosphere—is about 1 kg. This air weighs about 10 N.

SCREENCAST: Atmospheric Pressure

FIGURE 14.5
Ann Brandon fascinates her students when she rides on a cushion of air blown through a hole in the middle of this jumbo air puck.

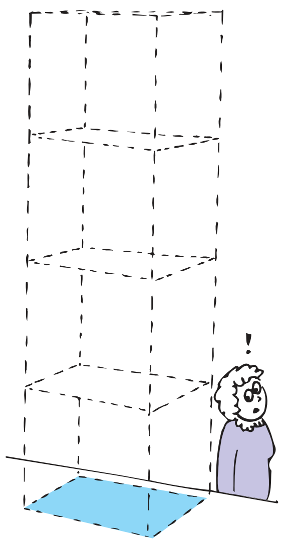

FIGURE 14.6
The weight of air bearing down on a 1-m^2 surface at sea level is about 100,000 N. In other words, atmospheric pressure is about 10^5 N/m^2, or about 100 kPa.

CHECK POINT

1. **About how many kilograms of air occupy a classroom that has a 200-m^2 floor area and a 4-m-high ceiling? (Assume a chilly temperature of 10°C.)**
2. **Why doesn't the pressure of the atmosphere break windows?**

VIDEO: Air Has Weight

VIDEO: Air Is Matter

[1]The pascal (1 N/m^2) is the SI unit of pressure. The average pressure at sea level (101.3 kPa) is often called 1 atmosphere. In British units, the average atmospheric pressure at sea level is 14.7 lb/in^2.

TABLE 14.1
DENSITIES OF VARIOUS GASES

Gas	Density (kg/m³)*
Dry air	
0°C	1.29
10°C	1.25
20°C	1.21
30°C	1.16
Hydrogen	0.090
Helium	0.178
Nitrogen	1.25
Oxygen	1.43

*At sea-level atmospheric pressure and at 0°C (unless otherwise specified)

CHECK YOUR ANSWERS

1. The mass of air is 1000 kg. The volume of air is area × height = 200 m^2 × 4 m = 800 m^3; each cubic meter of air has a mass of about 1.25 kg, so 800 m^3 × 1.25 kg/m^3 = 1000 kg.
2. Atmospheric pressure is exerted on both sides of a window, so no net force is exerted on the glass. If, for some reason, the pressure is reduced or increased on one side only, as when a tornado passes by, then watch out! Reduced outside air pressure created by a tornado can be disastrous.

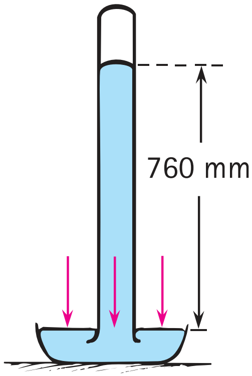

FIGURE 14.7
A simple mercury barometer.

The Barometer

In 1643, Italian physicist and mathematician Evangelista Torricelli found a way to measure the pressure that air exerts—he invented the first **barometer**. A simple mercury barometer is illustrated in Figure 14.7. It consists of a mercury-filled glass tube, somewhat longer than 76 cm, immersed in a dish (reservoir) of mercury. When Torricelli tipped the mercury-filled tube upside down and placed it mouth downward in a dish of mercury, the mercury in the tube dropped to a level at which the weight of the mercury in the tube was balanced by the atmospheric force exerted on the reservoir. The empty space trapped above, except for some mercury vapor, is a vacuum. The vertical height of the mercury column remains constant even when the tube is tilted, unless the top of the tube is less than 76 cm above the level in the dish—in which case the mercury completely fills the tube.

The balance of mercury in a barometer is similar to the way a playground seesaw balances when the torques of people at its two ends are equal. The barometer "balances" when the weight of the liquid in the tube exerts the same pressure as the atmosphere outside. Whatever the width of the tube, a 76-cm column of mercury weighs the same as the air that would fill a super-tall 30-km tube of the same width. If the atmospheric pressure increases, then the atmosphere pushes down harder on the mercury and the column of mercury is pushed higher than 76 cm. The mercury is literally pushed up into the tube of a barometer by the weight of the atmosphere. Atmospheric pressure is measured by the height of a mercury column on a barometer, and it is still often expressed in millimeters or inches of mercury. The more common scientific unit is the kilopascal.

Could water be used to make a barometer? The answer is *yes*, but the glass tube would have to be much longer—13.6 times as long, to be exact. You may recognize this number as the density of mercury relative to that of water. A volume of water 13.6 times that of mercury is needed to provide the same weight as the mercury in the tube. So the tube would have to be at least 13.6 times taller than the mercury column. A water barometer would have to be 13.6 × 0.76 m, or 10.3 m high—too tall to be practical.

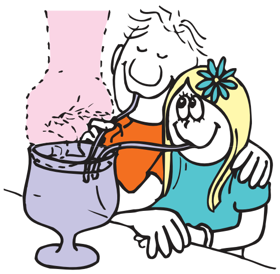

FIGURE 14.8
Strictly speaking, these two do not suck the soda up the straws. They instead reduce the pressure in the straws and allow the weight of the atmosphere to push the liquid up into the straws. Could they drink a soda this way on the Moon?

What happens in a barometer is similar to what happens during the process of drinking through a straw. By sucking on the straw placed in the drink, you reduce the air pressure in the straw. The weight of the atmosphere on the drink pushes liquid up into the reduced-pressure region inside the straw. Strictly speaking, the liquid is not sucked up; it is pushed up by the pressure of the atmosphere. If the atmosphere is prevented from pushing on the surface of the drink, as in the party-trick bottle with the straw passing through an airtight cork stopper, one can suck and suck and get no drink.

If you understand these ideas, you can understand why there is a 10.3-m limit on the height that water can be lifted with vacuum pumps. The old-fashioned farm-type pump, like the one shown in Figure 14.9, operates by producing a partial vacuum in a pipe that extends down into the water below. The weight of the

FIGURE 14.9
The atmosphere pushes water from below up into a pipe that is partially evacuated of air by the pumping action.

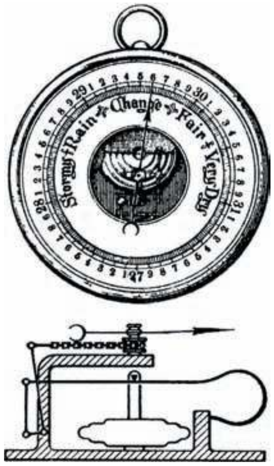

FIGURE 14.10
An aneroid barometer (top) and its cross-section (bottom).

When the handle is pumped, the air in the pipe is "thinned" as it expands to fill a larger volume. Atmospheric pressure on the well surface pushes water up into the pipe, causing water to overflow at the spout.

atmosphere on the surface of the water simply pushes the water up into the region of reduced pressure inside the pipe. Can you see that, even with a perfect vacuum, the maximum height to which water can be lifted is 10.3 m?

A small portable instrument that measures atmospheric pressure is the *aneroid barometer*. The classic model shown in Figure 14.10 uses a metal box that is partially exhausted of air and has a slightly flexible lid that bends in or out with changes in atmospheric pressure. The motion of the lid is indicated on a scale by a mechanical spring-and-lever system. Since the atmospheric pressure decreases with increasing altitude, a barometer can be used to determine elevation. An aneroid barometer calibrated for altitude is called an *altimeter* (altitude meter). Some altimeters are sensitive enough to indicate a change in elevation of less than a meter.

Vacuums are produced by pumps, which work by virtue of a gas tending to fill its container. If a space with lower pressure is provided, gas will flow from the region of higher pressure to the region of lower pressure. A vacuum pump simply provides a region of lower pressure into which fast-moving gas molecules randomly move. The air pressure is repeatedly lowered by piston and valve action (Figure 14.11). The best vacuums attainable with mechanical pumps are about 1 Pa. Better vacuums, down to 10^{-8} Pa, are attainable with vapor-diffusion or vapor-jet pumps. Sublimation pumps can reach 10^{-12} Pa. Greater vacuums are very difficult to attain.

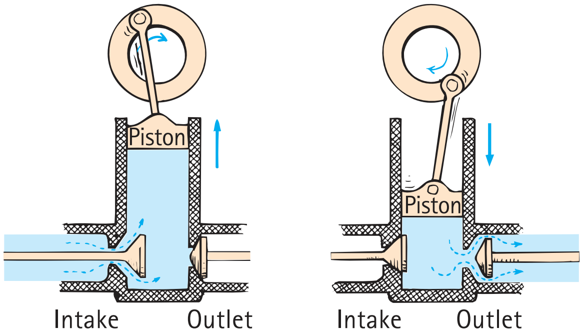

FIGURE 14.11
A mechanical vacuum pump. When the piston is lifted, the intake valve opens and air moves in to fill the empty space. When the piston is moved downward, the outlet valve opens and the air is pushed out. What changes would you make to convert this pump to an air compressor?

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- For international flights on aircraft, a cabin pressure of three-quarters normal atmospheric pressure is the lowest permitted.

CHECK POINT

What is the maximum height to which water can be sucked up through a straw?

CHECK YOUR ANSWER

At sea level, however strong your lungs may be, or whatever device you use to make a vacuum in the straw, the water cannot be pushed up by the atmosphere higher than 10.3 m.

14.3 Boyle's Law

The air pressure inside the inflated tires of an automobile is considerably higher than the atmospheric pressure outside. The density of the air inside is also greater than the density of the air outside. To understand the relationship between *pressure* and *density*, think of the molecules of air (primarily nitrogen and oxygen) inside the tire, which behave like tiny Ping-Pong balls—perpetually moving helter-skelter and banging against one another and against the inner walls. Their impacts produce a jittery force that appears to our coarse senses as a steady push. This pushing force averaged over a unit of area provides the pressure of the enclosed air.

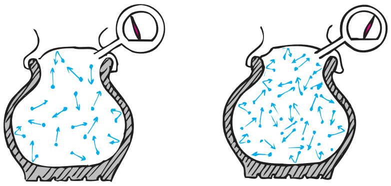

FIGURE 14.12
When the density of gas in the tire is increased, the pressure is increased.

Suppose that there are twice as many molecules in the same volume (Figure 14.12). Then the air density is doubled. If the molecules move at the same average speed—or, equivalently, if they have the same temperature—then the number of collisions is doubled. This means that the pressure is doubled. So pressure is proportional to density.

We can also double the air density by compressing the air to half its volume. Consider the cylinder with the movable piston in Figure 14.13. If the piston is pushed downward so that the volume is half the original volume, the density of molecules doubles and the pressure correspondingly doubles. Decrease the volume to a third of its original value, and the pressure increases by three, and so forth (provided that the temperature remains the same and the number of molecules remains the same).

Is the atmospheric pressure actually different over a few centimeters' difference in altitude? The fact that it is is demonstrated with any helium-filled balloon that rises in air. The atmospheric pressure up against the bottom surface of the balloon is greater than the atmospheric pressure down against the top.

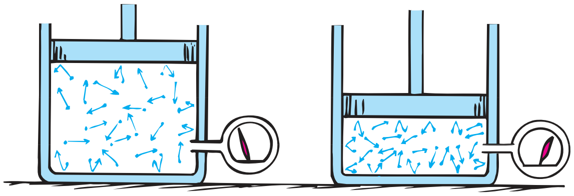

FIGURE 14.13
When the volume of a gas is decreased, its density and therefore pressure are increased.

VIDEO: Air Has Pressure

Notice in these examples involving pistons that *pressure and volume are inversely proportional*; if you double one, for example, you halve the other.[2] We can write this as

$$P \sim \frac{1}{V}$$

where P stands for pressure and V for volume. We can write this relationship as

$$PV = \text{constant}$$

Another way to express this is

$$P_1V_1 = P_2V_2$$

Here P_1 and V_1 represent the original pressure and volume, respectively, and P_2 and V_2 represent the second pressure and volume. Or, put more graphically,

$$pV = Pv$$

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- A tire pressure gauge at a service station doesn't measure absolute air pressure. A flat tire registers zero pressure on the gauge, but a pressure of about 1 atmosphere exists there. Gauges read "gauge" pressure—pressure greater than atmospheric pressure.

This relationship between pressure and volume is called **Boyle's law**, after physicist Robert Boyle, who, with the help of fellow physicist Robert Hooke, made this discovery in the 17th century. Boyle's law applies to ideal gases. An ideal gas is one in which the disturbing effects of the forces between molecules and the finite size of the individual molecules can be ignored. Air and other gases under normal pressures approach ideal-gas conditions.

SCREENCAST: Boyle's Law

[2]A general law that takes temperature changes into account is $P_1V_1/T_1 = P_2V_2/T_2$, where T_1 and T_2 represent the first and second *absolute* temperatures, measured in the SI unit called the *kelvin* (see Chapters 15 and 18).

CHECK POINT

1. **A piston in an airtight pump is withdrawn so that the volume of the air chamber is increased three times. What is the change in pressure?**
2. **A scuba diver 10.3 m deep breathes compressed air. If she holds her breath while returning to the surface, by how much will the volume of her lungs tend to increase?**

CHECK YOUR ANSWERS

1. The pressure in the piston chamber is reduced to one-third. This is the principle that underlies a mechanical vacuum pump.
2. Atmospheric pressure can support a column of water 10.3 m high, so the pressure in water due to its weight alone equals atmospheric pressure at a depth of 10.3 m. If we take the pressure of the atmosphere at the water's surface into account, the total pressure at this depth is twice atmospheric pressure. Unfortunately for the scuba diver, her lungs will tend to inflate to twice their normal size if she holds her breath while rising to the surface. A first lesson in scuba diving is not to hold your breath when ascending. To do so can be fatal.

Workers in underwater construction toil in an environment of compressed air. The air pressure in their underwater chambers is at least as high as the combined pressure of the water and the atmosphere outside.

14.4 Buoyancy of Air

A crab lives at the bottom of its ocean of water and looks upward at jellyfish floating above it. Similarly, we live at the bottom of our ocean of air and look upward at balloons drifting above us. A balloon is suspended in air and a jellyfish is suspended in water for the same reason: Each is buoyed upward by a displaced weight of fluid equal to its own weight. In one case, the displaced fluid is air; in the other case, it is water. As discussed in Chapter 13, objects in water are buoyed upward because the pressure that acts up against the bottom of the object exceeds the pressure that acts down against the top. Likewise, the air pressure that acts up against an object in air is greater than the air pressure above that pushes down. The buoyancy, in both cases, is numerically equal to the weight of the fluid displaced. **Archimedes' principle** holds for air just as it does for water:

An object surrounded by air is buoyed up by a force equal to the weight of the air displaced.

VIDEO: Buoyancy of Air

We know that a cubic meter of air at ordinary atmospheric pressure and room temperature has a mass of about 1.2 kg, so its weight is about 12 N. Therefore, any 1-m^3 object in air is buoyed up with a force of 12 N. If the mass of the 1-m^3 object is greater than 1.2 kg (so that its weight is greater than 12 N), it falls to the ground when released. If an object of this size has a mass less than 1.2 kg, it rises in the air. Any object that has a mass that is less than the mass of an equal volume of air will rise in air. Another way to say this is that any object less dense than air will rise in air. Gas-filled balloons that rise in air are less dense than air.

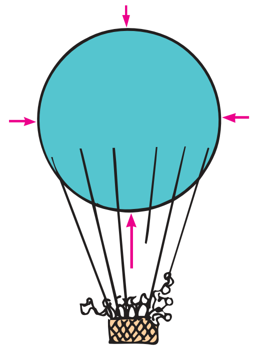

FIGURE 14.14
All bodies are buoyed up by a force equal to the weight of the air they displace. Why, then, don't all objects float like this balloon?

The greatest buoyancy would be achieved if a balloon were evacuated, but this isn't practical. The weight of a structure needed to keep an evacuated balloon from collapsing would more than offset the advantage of the extra buoyancy. So balloons are filled with gas less dense than ordinary air, which keeps the balloon from collapsing while keeping it light. In sport balloons, the gas is simply heated air. In balloons intended to reach very high altitudes or to stay up for a long time, helium is usually used. Its density is low enough so that the combined weight of helium, balloon, and whatever the cargo happens to be is less than the weight of the air it

SCREENCAST: Buoyancy of Balloons

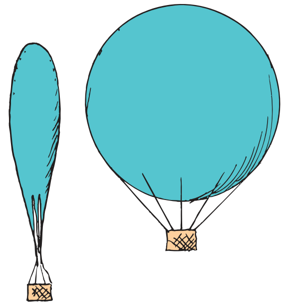

FIGURE 14.15
(Left) At ground level, the balloon is partially inflated. (Right) The same balloon is fully inflated at high altitudes where the surrounding pressure is lower.

displaces.[3] Low-density gas is used in a balloon for the same reason that cork or Styrofoam is used in a swimmer's life preserver. The cork or Styrofoam possesses no strange tendency to be drawn toward the surface of water, and the gas possesses no strange tendency to rise. Both are buoyed upward like anything else. They are simply light enough for the buoyancy to be significant.

Unlike water, the atmosphere has no definable surface. There is no "top." Furthermore, unlike water, the atmosphere becomes less dense with altitude. Whereas cork floats to the surface of water, a released helium-filled balloon does not rise to any atmospheric surface. How high will a balloon rise? We can state the answer in several ways. A gas-filled balloon will rise only so long as it displaces a weight of air greater than its own weight. Because air becomes less dense with altitude, a lesser weight of air is displaced per given volume as the balloon rises. Since most balloons expand as they rise, their buoyancy stays fairly constant until they can't expand anymore. When the weight of the displaced air equals the total weight of the balloon, the upward motion of the balloon will cease. We can also say that when the buoyant force on the balloon equals its weight, the balloon will cease rising. Equivalently, when the density of the balloon (including its load) equals the density of the surrounding air, the balloon will cease rising. Helium-filled toy balloons usually break when released in the air because the expansion of the helium they contain stretches the rubber until it ruptures. Large dirigible airships are designed so that when they are loaded, they will slowly rise in air; that is, their total weight is a little less than the weight of the air displaced. When in motion, the ship may be raised or lowered by means of horizontal "elevators."

Thus far, we have treated pressure only as it applies to stationary fluids. Motion produces an additional influence.

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- A typical good-sized cloud bank contains a million or so tons of water, all in the form of suspended water drops.

CHECK POINT

1. **Is there a buoyant force acting on you? If there is, why aren't you buoyed up by this force?**
2. **(This one calls for your best thinking!) How does buoyancy change as a helium-filled balloon ascends?**

CHECK YOUR ANSWERS

1. There is a buoyant force acting on you, and you *are* buoyed upward by it. You don't notice it only because your weight is so much greater.
2. If the balloon is free to expand as it rises, the increase in volume is counteracted by a decrease in the density of higher-altitude air. So, interestingly, the greater volume of displaced air doesn't weigh more, and buoyancy stays the same. If a balloon is not free to expand, buoyancy will decrease as a balloon rises because of the less-dense displaced air. Usually, balloons expand as they rise initially, and, if they don't finally rupture, the stretching of their fabric reaches a maximum, and they settle where their buoyancy matches their weight. As Figure 14.15 shows, high-altitude balloons appear very under-inflated at launch.

SCREENCAST: Air-Buoyancy Problems

14.5 Bernoulli's Principle

Consider a continuous flow of water through a pipe. Because water doesn't "bunch up," the amount of water that flows past any given section of the pipe is the same as the amount that flows past any other section of the same pipe—even if the pipe widens or narrows. For continuous flow, a fluid speeds up when it goes from a wide to a narrow

SCREENCAST: Bernoulli Principle

[3]Hydrogen is the least dense gas and was used in passenger-carrying balloons from the late 1700s to the mid-1900s. Because hydrogen is highly flammable, however, as evident in the Hindenburg disaster of 1937, it is seldom used anymore.

part of the pipe and slows down when it goes from a narrow part of the pipe. This is evident in a broad, slow-moving river that flows more swiftly as it enters a narrow gorge of much the same depth. It is also evident when water flowing from a garden hose speeds up when you squeeze the end of the hose to make the stream narrower.

This change of speed with changing cross-section is a consequence of what we call the principle of *continuity*, which is the subject of the two fyi's on this page. For flow to be continuous in a confined region, it speeds up when moving from a wider region to a narrower one.

The motion of a fluid in steady flow follows imaginary *streamlines*, represented by thin lines in Figure 14.17 and in other figures that follow. Streamlines are the smooth paths of bits of fluid. The lines are closer together in narrower regions, where the flow speed is greater. (Streamlines are visible when smoke or other visible fluids are passed through evenly spaced openings, as in a wind tunnel.)

Daniel Bernoulli, an 18th-century Swiss scientist, studied fluid flow in pipes. His discovery, now called **Bernoulli's principle**, can be stated as follows:

> **Where the speed of a fluid increases, the internal pressure in the fluid decreases.**

And vice versa: Where the speed decreases, the internal pressure increases. This applies when friction, turbulence, and changes in height don't affect pressure. The principle holds for smooth flow along streamlines.

Where streamlines of a fluid are closer together, flow speed is greater and pressure within the fluid is lower. Changes in internal pressure are evident in water that contains air bubbles (Figure 14.18). The volume of an air bubble depends on the surrounding water pressure. Where water gains speed, pressure is lowered and the bubbles become bigger. In water that slows, pressure is increased and the bubbles are squeezed to a smaller size.

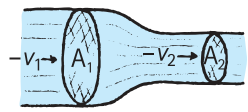
FIGURE 14.16
Because the flow is continuous, water speeds up when it flows through the narrow and/or shallow part of the brook.

fyi

- Because the volume of water flowing through a pipe of different cross-sectional areas A remains constant, the speed of flow v is high where the area is small and the speed is low where the area is large. This is stated in the equation of continuity:

$$A_1v_1 = A_2v_2$$

The product A_1v_1 at any point 1 equals the product A_2v_2 at point 2.



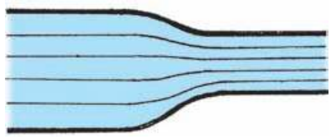


FIGURE 14.17
Water speeds up when it flows into the narrower pipe. The close-together streamlines indicate increased speed and decreased internal pressure.

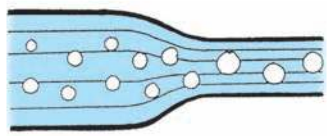


FIGURE 14.18
Internal pressure is higher in slower-moving water in the wide part of the pipe, as evidenced by the more-squeezed air bubbles. The bubbles are bigger in the narrow part because the internal pressure there is lower.

One way to greatly increase the pressure in a fluid is to rapidly bring it to rest (to what is called the *stagnation pressure*). If you have ever had the misfortune to be struck by a water cannon, you have experienced the effect. Recall from Chapter 6 that a large change in momentum is associated with a large impulse. So when water from a water cannon hits you, the impulse can knock you off your feet. A high-speed jet of water can even be used to cut steel in modern machine shops.

Bernoulli's principle is a consequence of the conservation of energy, although, surprisingly, he developed it long before the concept of energy was formalized.[4] The principle also follows from Newton's second law of motion. In either case, Bernoulli's principle applies to a smooth, steady flow (called *laminar* flow) of

fyi

- If you've wondered how slight breezes turn into brisk winds at the top of hills, think of the principle of continuity! Although there is no pipe to constrain the airflow, it is nevertheless similarly constrained and speeds up.

[4]In mathematical form: $1/2mv^2 + mgy + pV =$ constant (along a streamline); where m is the mass of some small volume V, v its speed, g the acceleration due to gravity, y its elevation, and p its internal pressure. If mass m is expressed in terms of density, ρ, where $\rho = m/V$, and each term is divided by V, Bernoulli's equation reads: $1/2\rho v^2 + \rho gy + p =$ constant. Then all three terms have units of pressure. If y does not change, an increase in v means a decrease in p, and vice versa. Note when v is zero Bernoulli's equation reduces to $\Delta p = -\rho g\Delta y$ (weight density $\times$ depth).

A fire hose is fat when it is not spurting water. When the water is turned on and the hose spurts, why does it become thinner?

constant-density fluid. At speeds greater than some critical point, however, the flow may become chaotic (called *turbulent* flow) and follow changing, curling paths called *eddies*. This exerts friction on the fluid and dissipates some of its energy. Then Bernoulli's equation doesn't apply well.

The full energy picture for a fluid in motion is quite complicated. Simply stated, greater speed and greater kinetic energy mean lower pressure, while higher pressure means lower speed and lower kinetic energy.

Applications of Bernoulli's Principle

Anyone who has ridden in a convertible car with the canvas top up has noticed that the roof puffs upward as the car moves. This is Bernoulli in action! The pressure outside against the top of the fabric, where air has speeded up in moving up and over the car, is lower than the static atmospheric pressure inside the car. The result is an upward net force on the fabric.

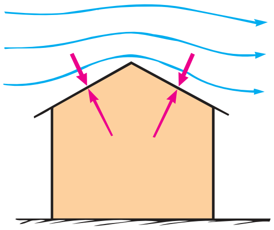


FIGURE 14.19
The air pressure above the roof is lower than the air pressure beneath the roof.

Consider wind blowing across a peaked roof. Just as liquid gains speed when it enters a constricted pipe, the wind gains speed as it is similarly constricted in flowing up and over the roof. Its gain of speed is indicated by the crowding of streamlines in Figure 14.19. The pressure along the streamlines is reduced where they are closer together. The greater pressure inside the roof can lift it off the house. During a severe storm, the difference in outside and inside pressures doesn't need to be very great. A small pressure difference over a large area produces a force that can be formidable.

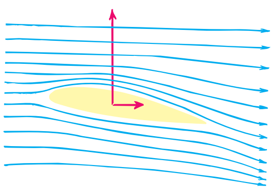


FIGURE 14.20
The vertical vector represents the net upward force (lift) that results from higher air pressure below the wing than above the wing. The horizontal vector represents air drag.

If we think of the blown-off roof as an airplane wing, we can better understand the lifting force that supports a heavy aircraft. In both cases, a higher pressure below pushes the roof or the wing into a region of lower pressure above. Wings come in a variety of designs. What they all have in common is that air is made to flow faster over the wing's top surface than under its lower surface. This is mainly accomplished by a tilt in the wing, called its *angle of attack*. Then air flows faster over the top surface for much the same reason that air flows faster in a narrowed pipe or in any other constricted region. Often, but not always, different speeds of airflow over and beneath a wing are enhanced by a difference in the curvature (*camber*) of the upper and lower surfaces of the wing. The result is more crowded streamlines along the top wing surface than along the bottom. When the average pressure difference over the wing is multiplied by the surface area of the wing, we have a net upward force—lift.[5] Lift is greater when there is a large wing area and when the plane is traveling fast. A glider has a very large wing area relative to its weight, so it does not have to be going very fast for sufficient lift. At the other extreme, a fighter plane designed for high-speed flight has a small wing area relative to its weight. Consequently, it must take off and land at high speeds.

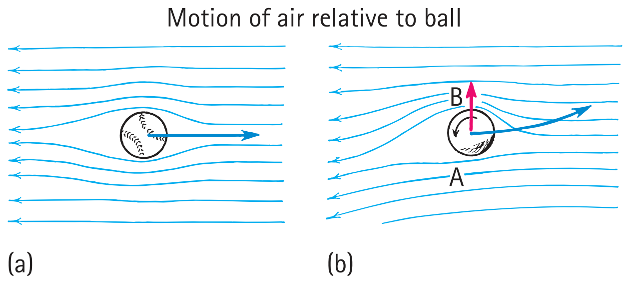


FIGURE 14.21
(a) The streamlines are the same on either side of a nonspinning baseball. (b) A spinning ball produces a crowding of streamlines. The resulting "lift" (red arrow) causes the ball to curve, as shown by the blue arrow.

We all know that a baseball pitcher can impart a spin on a ball to make it curve off to one side as it approaches home plate. Similarly, a tennis player can hit a ball so that it curves. A thin layer of air is dragged around the spinning ball by friction, which is enhanced by the baseball's threads or the tennis ball's fuzz.[6] The moving layer of air produces a crowding of streamlines on one side. Note in Figure 14.21b that the

[5]Pressure differences are only one way to understand wing lift. Another way uses Newton's third law. The wing forces air downward (action), and the air forces the wing upward (reaction). Air is deflected downward by the wing tilt, the angle of attack—even when flying upside down! When riding in a car, place your hand out the window and pretend it's a wing. Tip it up slightly so air is forced downward. Up goes your hand! Air lift provides a nice example to remind us that there is often more than one way to explain the behavior of nature.

[6]Strictly speaking, Bernoulli's principle applies to fluid flow devoid of friction. If you study the curving of balls further, look into the Magnus effect, which deals with friction and viscosity.

PRACTICING PHYSICS

Fold the end of a filing card down to make a little bridge or tunnel. Place it on a table and blow through the arch as shown. No matter how hard you blow, you will not succeed in blowing the card off the table (unless you blow against the side of it). Try this with your friends who have not taken physics. Then explain it to them!

streamlines are more crowded at B than at A for the direction of spin shown. Air pressure is greater at A, and the ball curves as shown.

Recent findings show that many insects increase their lift by employing motions similar to those of a curving baseball. Interestingly, most insects do not flap their wings up and down. They flap them forward and backward, with a tilt that provides an angle of attack. Between flaps, their wings make semicircular motions to create lift.

A familiar hand-operated sprayer utilizes Bernoulli's principle (Figure 14.22). When you push a plunger, air is forced from a wider to a narrower channel and emerges with lower than normal atmospheric pressure above the open end of a tube inserted into the flow of liquid. Atmospheric pressure on the liquid below then pushes the liquid up into the tube, where it is carried away by the stream of air.

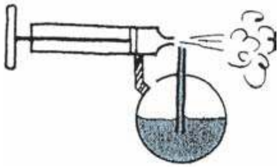


FIGURE 14.22
Why does the liquid in the reservoir go up the tube?

Bernoulli's principle explains why trucks that pass closely on the highway are drawn toward each other, and why passing ships run the risk of a sideways collision. Water that flows between the ships travels faster than water that flows past the outer sides. Streamlines are closer together between the ships than outside, so the water pressure that acts against the hulls is reduced between the ships. Even a slight reduction of pressure against the relatively huge surface area at the sides of the ships can produce significant force. Unless the ships are steered to compensate for this, the greater pressure against the outer sides of the ships forces them together. Figure 14.23 shows how to demonstrate this in your kitchen sink or bathtub.

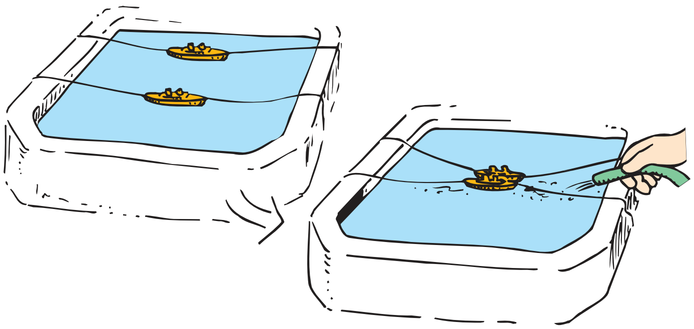


FIGURE 14.23
Loosely moor a pair of toy boats side by side in your sink. Then direct a stream of water between them. The boats will draw together and collide. Why?

Bernoulli's principle plays a small role when your bathroom shower curtain swings toward you in the shower when the water is on full blast. The pressure in the shower stall is slightly reduced with fluid in motion, and the relatively greater pressure outside the curtain pushes it inward. Like so much in the complex real world, this is but one physics principle that applies in this situation. More important is the convection of air in the shower. In any case, the next time you're taking a shower and the curtain swings in against your legs, think of Daniel Bernoulli.

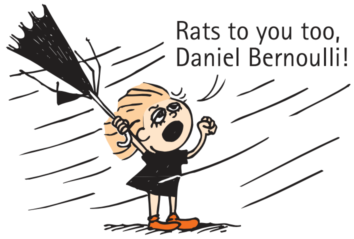
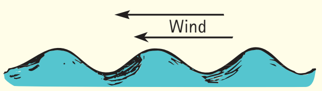


FIGURE 14.24
The curved shape of an umbrella can be disadvantageous on a windy day.

CHECK POINT

A windy day makes for waves in a lake or the ocean. How does Bernoulli's principle assist in creating higher waves?



CHECK YOUR ANSWER

The troughs of the waves are partially shielded from the wind, so air travels faster over the crests. Pressure over the crests is therefore lower than down below in the troughs. The higher pressure in the troughs aids in pressing water up into the crests.

SCREENCAST: Bernoulli Applications

14.6 Plasma

In addition to solids, liquids, and gases, there is a fourth phase of matter—**plasma** (not to be confused with the clear liquid part of blood, also called plasma). Plasma is the least common phase in our everyday environment, but it is the most prevalent phase of matter in the universe as a whole. The Sun and other stars are largely plasma.

A plasma is an electrified gas. The atoms that make it up are *ionized*, stripped of one or more electrons, with a corresponding number of free electrons. Recall that a neutral atom has as many positive protons inside the nucleus as it has negative electrons outside the nucleus. When one or more of these electrons is stripped from the atom, the atom has more positive charge than negative charge and becomes a *positive ion*. (Under some conditions, it may have extra electrons—in which case it is a *negative ion*.) Although the electrons and ions are themselves electrically charged, the plasma as a whole is electrically neutral because there are still equal numbers of positive and negative charges, just as there are in an ordinary gas. Nevertheless, a plasma and a gas have very different properties. The plasma readily conducts electric current, absorbs certain kinds of radiation that pass unhindered through a gas, and can be shaped, molded, and moved by electric and magnetic fields.

Our Sun is a ball of hot plasma. Plasmas on Earth are created in laboratories by heating gases to very high temperatures, making them so hot that electrons are "boiled" off the atoms. Plasmas may also be created at lower temperatures by bombarding atoms with high-energy particles or radiation.

FIGURE 14.25
Streets are illuminated at night by glowing plasmas.

Plasma in the Everyday World

If you're reading this by light emitted by a fluorescent lamp or a compact fluorescent bulb, you don't have to look far to see plasma in action. Within the glowing tube is plasma that contains argon and mercury ions (as well as many neutral atoms of these elements). When you turn the lamp on, a high voltage between electrodes at each end of the tube causes electrons to flow. These electrons ionize some atoms, forming plasma, which provides a conducting path that keeps the current flowing. The current activates some mercury atoms, causing them to emit radiation, mostly in the invisible ultraviolet region. This radiation causes the phosphor coating on the tube's inner surface to glow with visible light.

Similarly, the neon gas in an advertising sign becomes a plasma when its atoms are ionized by electron bombardment. Neon atoms, after being activated by electric current, emit predominantly red light. The different colors seen in these signs correspond to plasmas made up of different kinds of atoms. Argon, for example, glows blue, and helium glows pink. Sodium vapor lamps used in street lighting emit yellow light stimulated by glowing plasmas (Figure 14.25).

Flat plasma TV screens are composed of many thousands of pixels, each of which is composed of three separate subpixel cells. One cell has a phosphor that fluoresces red, another has a phosphor that fluoresces green, and the other blue. The pixels are sandwiched in a network of electrodes that are charged thousands of times in a small fraction of a second, producing electric currents that flow through gases in the cells. As in a fluorescent lamp, the gases convert to glowing plasmas that release ultraviolet light that stimulates the phosphors. The image on the screen is the blend of pixel colors activated by the TV control signal.

FIGURE 14.26
In a plasma TV, hundreds of thousands of tiny pixels are lit up red, green, and/or blue by glowing plasmas. These colors are combined in different proportions to produce the entire color spectrum.

The aurora borealis and the aurora australis (called the northern and southern lights, respectively) are glowing plasmas in the upper atmosphere. Layers of low-temperature plasma encircle the whole Earth. Occasionally, showers of electrons from outer space and radiation belts enter "magnetic windows" near Earth's poles, crashing into the layers of plasma and producing light.

Plasma Power

A higher-temperature plasma is the exhaust of a jet engine, a weakly ionized plasma. But when small amounts of potassium salts or cesium metal are added, it becomes a very good conductor and, when directed into a magnet, can generate electricity! This is MHD power, the **m**agneto**h**ydro**d**ynamic interaction between a plasma and a magnetic field. (We will discuss the mechanics of generating electricity in this way in Chapter 25.) Low-pollution MHD power is being used in a few places in the world already. Looking forward, perhaps we will see more plasma power with MHD.

An even more promising achievement will be plasma power of a different kind—the controlled fusion of atomic nuclei. We will treat the physics of fusion in Chapter 34. The benefits of controlled fusion may be far-reaching. Fusion power may not only make electric energy abundant but also provide the energy and means to recycle and even synthesize elements.

Humankind has come a long way with the mastery of the first three phases of matter. Our mastery of the fourth phase may bring us much further.

fyi

- High-frequency radio and TV waves pass through the atmosphere and out into space. Hence you have to be in the "line of sight" of broadcasting or relay antennas to pick up FM and TV signals. But layers of plasma some 80 km high, which make up the ionosphere, reflect lower-frequency radio waves. That explains why you can pick up radio stations long distances away on your lower-frequency AM radio. At night, when the plasma layers are settled closer together and are more reflective, you can sometimes receive very distant stations on your AM radio.

For instructor-assigned homework, go to www.masteringphysics.com MP

SUMMARY OF TERMS (KNOWLEDGE)

Atmospheric pressure The pressure exerted against bodies immersed in the atmosphere. It results from the weight of air pressing down from above. At sea level, atmospheric pressure is about 101 kPa.

Barometer A device that measures atmospheric pressure.

Boyle's law The product of pressure and volume is a constant for a given mass of confined gas, as long as the temperature remains unchanged:

$$P_1V_1 = P_2V_2$$

Archimedes' principle (for air) An object in the air is buoyed up with a force equal to the weight of the displaced air.

Bernoulli's principle Where the speed of a fluid increases, the internal pressure in the fluid decreases.

Plasma An electrified gas that contains ions and free electrons. Most of the matter in the universe is in the plasma phase.

READING CHECK QUESTIONS (COMPREHENSION)

14.1 The Atmosphere

1. What is the energy source for the motion of gas in the atmosphere? What prevents atmospheric gases from flying off into space?
2. What percentage of the atmosphere is below an altitude of 11 km? How will the percentage change if the altitude is 18 km?

14.2 Atmospheric Pressure

3. Why do we not feel atmospheric pressure?
4. What would be the approximate mass of 1m^3 of air at an altitude of 10 km?
5. What is the approximate mass of a column of air 1 cm^2 in area that extends from sea level to the upper atmosphere? What is the weight of this amount of air?
6. What is the pressure at the bottom of the column of air referred to in the preceding question?
7. How does the pressure at the bottom of a 76-cm column of mercury in a barometer compare with the air pressure at the bottom of the atmosphere?
8. How does the weight of mercury in a barometer compare with the weight of an equal cross-section of air from sea level to the top of the atmosphere?
9. Why would a barometer, constructed using water, be too tall to be practical for use?
10. Why do we have to suck on a straw if atmospheric pressure is responsible for the rising liquid? Give an example to prove that sucking on a straw alone will not always result in a rising column of liquid.
11. Why won't a vacuum pump operate for a well that is deeper than 10.3 m?
12. How does an aneroid barometer respond to any change in atmospheric pressure? What is an altimeter?

14.3 Boyle's Law

13. How much should the volume of a given amount of air be reduced to increase its density by a factor of 3?
14. What happens to the air pressure inside a balloon when it is squeezed to half its volume at constant temperature?
15. Does a flat tire have any pressure?

14.4 Buoyancy of Air

16. A balloon that weighs 1 N is suspended in air, drifting neither up nor down. (a) How much buoyant force acts on it? (b) What happens if the buoyant force decreases? (c) If it increases?
17. What is the buoyant force experienced in air by an object of 1-m^3 volume? What happens if the object weighs more than the buoyant force?
18. Why are balloons filled with a gas less dense than ordinary air?

14.5 Bernoulli's Principle

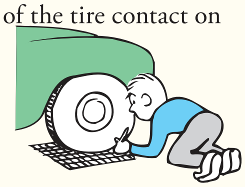
19. What do close-together streamlines indicate?
20. Is pressure greater or less in regions where streamlines are crowded?
21. What happens to the internal pressure in a fluid flowing in a horizontal pipe when its speed increases?
22. How does the size of air bubbles vary when the speed of the flowing water—containing the bubbles— is increased?
23. Does Bernoulli's principle refer to changes in the internal pressure of a fluid or to pressures the fluid may exert on objects?
24. Why does a fighter plane need to move at high speeds to generate sufficient lift?
25. How does faster-moving water between two ships affect the water pressure against the sides of the ships?
26. Are the ships in the preceding question sucked together or pushed together? Explain.
27. Is the fluid that goes up the inside tube in a hand sprayer pushed up the tube or sucked up the tube? Explain.

14.6 Plasma

28. How does a plasma differ from a gas?
29. Cite at least three examples of plasma in your daily environment.
30. What can be produced when a plasma beam is directed into the field of a strong magnet?

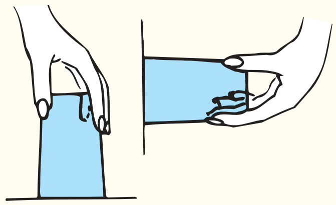
THINK AND DO (HANDS-ON APPLICATION)

31. Compare the pressure exerted by the tires of your car on the road with the air pressure in the tires. For this project, you need to know the weight of your car, which you can get from a manual or a dealer. You divide the weight by 4 to get the approximate weight held up by one tire. You can closely approximate the area of contact of a tire with the road by tracing the edges of the tire contact on a sheet of paper marked with 1-inch squares beneath the tire. After you calculate the pressure of the tire against the road, compare it with the air pressure in the tire. Are they nearly equal? If not, which is greater?

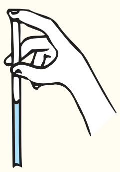


32. You ordinarily pour water from a full glass into an empty glass simply by placing the full glass above the empty glass and tipping. Have you ever poured air from one glass into another? The procedure is similar. Lower two glasses in water, mouths downward. Let one fill with water by tilting its mouth upward. Then hold the water-filled glass mouth downward above the air-filled glass. Slowly tilt the lower glass and let the air escape, filling the upper glass. You will be pouring air from one glass into another!

33. Raise a submerged upside-down glass that is full of water above the waterline, but with its mouth beneath the surface. Why doesn't the water run out? How tall would a glass have to be before water began to run out? (You won't be able to do this indoors unless you have a ceiling that is at least 10.3 m higher than the waterline.)
34. Place a card over the open top of a glass filled to the brim with water and invert it. Why does the card stay in place? Try it sideways.

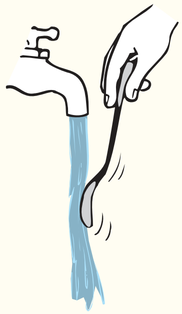


35. Invert a water-filled pop bottle or a small-necked jar. Notice that the water doesn't simply fall out but gurgles out of the container. Air pressure won't let it escape until some air has pushed its way up inside the bottle to occupy the space above the liquid. How would an inverted, water-filled bottle empty on the Moon?
36. Heat a small amount of water to boiling in an aluminum soda-pop can and invert it quickly into a dish of cooler water. Surprisingly dramatic!
37. Lower a narrow glass tube or drinking straw into water and place your finger over the top of the tube. Lift the tube from the water and then lift your finger from the top of the tube. What happens? (You'll do this often if you enroll in a chemistry lab.)



38. Push a pin through a small card and place it in the hole of a thread spool. Try to blow the card from the spool by blowing through the hole, as Evan Jones does in one of the chapter-opening photos. Try it in all directions.

39. Hold a spoon in a stream of water as shown and feel the effect of the differences in pressure.



THINK AND SOLVE (MATHEMATICAL APPLICATION)

40. Estimate the buoyant force that air exerts on you. (To do this, you can estimate your volume by knowing your weight and by assuming that your weight density is a bit less than that of water.)
41. A mountain-climber friend with a mass of 80 kg ponders the idea of attaching a helium-filled balloon to himself to effectively reduce his weight by 25% when he climbs. He wonders what the approximate size of such a balloon would be. Hearing of your physics skills, he asks you. Share with him your calculations that show the volume of the balloon to be about 17 m^3 (slightly more than 3 m in diameter for a spherical balloon).
42. On a perfect fall day, you are hovering at low altitude in a hot-air balloon, accelerated neither upward nor downward. The total weight of the balloon, including its load and the hot air in it, is 20,000 N.
    a. Show that the weight of the displaced air is 20,000 N.
    b. Show that the volume of the displaced air is 1700 m^3.
43. An airplane has a total wing surface of 200 square meters. The airplane requires a lift of 500,000 N to take off. What should be the difference in the air pressure between the bottom and top surface of the wings to produce this lift?
44. The weight of the atmosphere above 1 square meter of Earth's surface is about 100,000 N. Density, of course, decreases with altitude. But suppose the density of air were a constant 1.2 kg/m^3. Calculate where the top of the atmosphere would be.

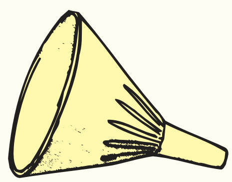
THINK AND RANK (ANALYSIS)

45. Rank the volumes of air in the glass, from greatest to least, when it is held
    a. near the surface as shown.
    b. 1 m beneath the surface.
    c. 2 m beneath the surface.

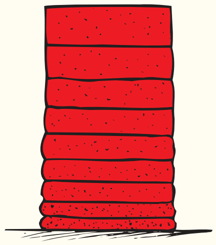
46. Rank the buoyant forces supplied by the atmosphere on the following, from greatest to least:
    a. An elephant
    b. A helium-filled party balloon
    c. A skydiver at terminal velocity
47. Rank from most to least, the amounts of lift on the following airplane wings:
    a. Area 1000 m^2 with an atmospheric pressure difference of 2.0 N/m^2
    b. Area 800 m^2 with an atmospheric pressure difference of 2.4 N/m^2
    c. Area 600 m^2 with an atmospheric pressure difference of 3.8 N/m^2

THINK AND EXPLAIN (SYNTHESIS)

48. What are the two competing factors that go to determine the thickness of the atmosphere on any planet?
49. Would there be an atmosphere if gravity was 'turned off'?
50. Why is the pressure in an automobile's tires slightly greater after the car has been driven several kilometers?
51. The valve stem on a tire must exert a certain force on the air within to prevent any of that air from leaking out. If the diameter of the valve stem were doubled, by how much would the force exerted by the valve stem increase?
52. Why is a soft, underinflated football at sea level much firmer when it is taken to a high elevation in the mountains?
53. What is the purpose of the ridges that prevent the funnel from fitting tightly in the mouth of a bottle?



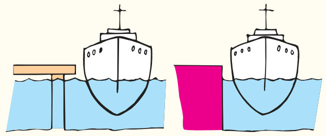
54. How does the density of air in a deep mine compare with the air density at Earth's surface?
55. When an air bubble rises in water, what happens to its mass, volume, and density?
56. Why do you suppose that airplane windows are smaller than bus windows?
57. We can understand how pressure in water depends on depth by considering a stack of bricks. The pressure below the bottom brick is determined by the weight of the entire stack. Halfway up the stack, the pressure is half because the weight of the bricks above is half. To explain atmospheric pressure, we should consider compressible bricks, like those made of foam rubber. Why is this so?



58. The "pump" in a vacuum cleaner is merely a high-speed fan. Would a vacuum cleaner pick up dust from a rug on the Moon? Explain.
59. Suppose that the pump shown in Figure 14.9 operated with a perfect vacuum. From how deep a well could water be pumped?
60. If a liquid only half as dense as mercury were used in a barometer, how high would its level be on a day of normal atmospheric pressure?
61. Why doesn't the size of the cross-sectional area of a mercury barometer affect the height of the enclosed mercury column?
62. Why does plasma conduct electric current if it is electrically neutral?
63. If you could somehow replace the mercury in a mercury barometer with a denser liquid, would the height of the liquid column be greater than or less than the height of the mercury? Why?
64. Would it be slightly more difficult to draw soda through a straw at sea level or on top of a very high mountain? Explain.
65. Why is it so difficult to breathe when snorkeling at a depth of 1 m and practically impossible at a 2-m depth? Why can't a diver simply breathe through a hose that extends to the surface?
66. A little girl sits in a car at a traffic light holding a helium-filled balloon. The windows are closed and the car is relatively airtight. When the light turns green and the car accelerates forward, her head pitches backward but the balloon pitches forward. Explain why.

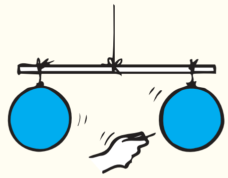
67. How does the concept of buoyancy complicate the old question "Which weighs more: a pound of lead or a pound of feathers?"
68. Why does a precision scale give different readings for the weight of an object in air and in a vacuum (remembering that weight is the force exerted against a supporting surface)? Cite an example in which this would be an important consideration.
69. Would a bottle of helium gas weigh more or less than an identical bottle filled with air at the same pressure? Than an identical bottle with the air pumped out?
70. When you replace helium in a balloon with less-dense hydrogen, does the buoyant force on the balloon change if the balloon remains the same size? Explain.
71. A steel tank filled with helium gas doesn't rise in air, but a balloon containing the same helium rises easily. Why?
72. If the number of gas atoms in a container is doubled, the pressure of the gas doubles (assuming constant temperature and volume). Explain this pressure increase in terms of the molecular motion of the gas.
73. What change in pressure occurs in a party balloon that is squeezed to one-third its volume with no change in temperature?
74. What, if anything, happens to the volume of gas in an atmospheric research-type balloon when it is heated?
75. What, if anything, happens to the pressure of the gas in a rubber balloon when the balloon is squeezed smaller?
76. What happens to the size of the air bubbles released by a diver as they rise?
77. You and your friendly car dealer float a long string of closely spaced helium-filled balloons over his used-car lot. You secure the two ends of the long string of balloons to different points on the ground so that the balloons float over the lot in an arc. What is the name of this arc? (Why could this exercise have been included in Chapter 12?)
78. The gas pressure inside an inflated rubber balloon is always greater than the air pressure outside. Explain.
79. The force of the atmosphere at sea level against the outside of a 10-m^2 store window is about a million N. Why doesn't this shatter the window? Why might the window shatter in a strong wind blowing past the window?
80. Why does the fire in a fireplace burn more briskly on a windy day?
81. What happens to the pressure in water as it speeds up when it is ejected by the nozzle of a garden hose?
82. Why do airplanes normally take off facing the wind?
83. What provides the lift to keep a Frisbee in flight?
84. When a steadily flowing gas flows from a larger-diameter pipe to a smaller-diameter pipe, what happens to (a) its speed, (b) its pressure, and (c) the spacing between its streamlines?
85. Compare the spacing of streamlines around a tossed baseball that doesn't spin in flight with the spacing of streamlines around a ball that does. Why does the spinning baseball veer from the course of a nonspinning one?
86. Why is it easier to throw a curve with a tennis ball than a baseball?

87. Why do airplanes extend wing flaps that increase the area and the angle of attack of the wing during takeoffs and landings? Why are these flaps pulled in when the airplane has reached cruising speed?
88. How is an airplane able to fly upside down?
89. Why are runways longer for takeoffs and landings at high-altitude airports, such as those in Denver and Mexico City?
90. How will two dangling vertical sheets of paper move when you blow between them? Try it and see.
91. What physics principle underlies these three observations? When passing an oncoming truck on the highway, your car tends to sway toward the truck. The canvas roof of a convertible car bulges upward when the car is traveling at high speeds. The windows of older trains sometimes break when a high-speed train passes by on the next track.
92. Wharves are made with pilings that permit the free passage of water. Why would a solid-walled wharf be disadvantageous to ships attempting to pull alongside?



THINK AND DISCUSS (EVALUATION)

93. If you count the tires on a large tractor-trailer that is unloading food at your local supermarket, you may be surprised to count 18 tires. Why so many tires? (*Hint*: Consider Think and Do #31.)
94. Two teams of eight horses each were unable to pull the Magdeburg hemispheres apart (shown on the opening page of this chapter). Suppose that two teams of nine horses each could pull them apart. Then would one team of nine horses succeed if the other team were replaced with a strong tree? Discuss this and defend your answer.
95. When boarding an airplane, you bring a bag of chips (or any other item packaged in an airtight foil package) and, while you are in flight, you notice that the bag puffs up. Discuss why this happens.
96. The pressure exerted against the ground by an elephant's weight distributed evenly over its four feet is less than 1 atmosphere. Discuss why it is that you'd be crushed beneath the foot of an elephant, while you're unharmed by the pressure of the atmosphere?
97. Your friend says that the buoyant force of the atmosphere on an elephant is significantly greater than the buoyant force of the atmosphere on a small helium-filled balloon. Discuss your response.
98. Discuss which will register the greater weight: an empty flattened balloon or the same balloon filled with air. Defend your answer: then try it and see.
99. On a sensitive balance, weigh an empty, flat, thin plastic bag. Then weigh the bag filled with air. Discuss whether or not the readings differ.
100. Two identical balloons of the same volume are pumped up with air to more than atmospheric pressure and suspended on the ends of a stick that is horizontally balanced. One of the balloons is then punctured. Discuss whether or not the balance of the stick is upset. If so, which way does it tip?



101. Two balloons that have the same weight and volume are filled with equal amounts of helium. One is rigid and the other is free to expand as the pressure outside decreases. When released, discuss which will rise higher.
102. A helium-filled balloon and a basketball have the same volume. Upon which is the buoyant force of the surrounding air greater? Discuss why the balloon is at the ceiling of a room whereas the basketball is on the floor.
103. Imagine a huge space colony that consists of a rotating air-filled cylinder. Discuss how the density of the air at "ground level" would compare to the air densities "above."
104. Discuss whether or not a helium-filled balloon could "rise" in the atmosphere of a rotating space habitat.
105. Discuss whether or not lower pressure is the result of fast-moving air, or fast-moving air is the result of lower pressure. Give one example supporting each point of view. (In physics, when two things are related—such as force and acceleration or speed and pressure—it is usually arbitrary which one we call *cause* and which one we call *effect*.)

PART TWO Multiple-Choice Practice Exam

Choose the BEST answer to each of the following:

1. If two protons and two neutrons are removed from the nucleus of neon-20, a nucleus of which element remains?
(a) Magnesium-22
(b) Magnesium-20
(c) Oxygen-18
(d) Oxygen-16
2. The nucleus of an electrically neutral iron atom contains 26 protons. The number of electrons this iron atom has is
(a) 52.
(b) 26.
(c) 24.
(d) None.
3. How many electrons are there in the third shell of sodium, Na (atomic number 11)?
(a) None
(b) One
(c) Two
(d) Three
4. The crystals that make up minerals are composed of
(a) atoms with a definite geometrical arrangement.
(b) molecules that perpetually move.
(c) X-ray patterns.
(d) 3-dimensional chessboards.
5. If the volume of an object were to double, with no change in mass, its density would
(a) halve.
(b) double.
(c) be the same.
(d) None of these.
6. According to Hooke's law, if you hang by a tree branch and note how much it bends, then hanging with twice the weight produces
(a) half the bend.
(b) the same bend if the branch doesn't break.
(c) twice the bend.
(d) 4 times the bend.
7. When you bend the branch of a tree by hanging on its end, the top side of the branch is under
(a) tension.
(b) compression.
(c) Both.
(d) Neither.
8. When you scale up an object to 3 times its linear size, the surface area increases by
(a) 3 and the volume by 9.
(b) 3 and the volume by 27.
(c) 9 and the volume by 27.
(d) 4 and the volume by 8.
9. Pumice is a volcanic rock that floats in water. The density of pumice compared with that of water is
(a) less.
(b) equal.
(c) greater.
(d) none because it sinks.
10. The pressure at the bottom of a pond does NOT depend on the
(a) acceleration due to gravity.
(b) water density.
(c) depth of the pond.
(d) surface area of the pond.
11. A completely submerged object always displaces its own
(a) weight of fluid.
(b) volume of fluid.
(c) density of fluid.
(d) All of these.
12. A rock suspended by a weighing scale weighs 5 N out of water and 3 N when submerged in water. What is the buoyant force on the rock?
(a) 3 N
(b) 5 N
(c) 8 N
(d) None of these.
13. In a vacuum, an object has no
(a) buoyant force.
(b) mass.
(c) weight.
(d) All of these.
14. Atmospheric pressure is due to the weight
(a) of the atmosphere.
(b) and volume of the atmosphere.
(c) density and volume of the atmosphere.
(d) of planet Earth itself.
15. Consider two mercury barometers, one having a cross-sectional area of 1 cm^2 and the other 2 cm^2. The height of mercury in the narrower tube is
(a) half.
(b) twice.
(c) the same.
(d) None of these.
16. A barometer that uses water instead of mercury will be
(a) shorter.
(b) taller.
(c) equal in height.
(d) inoperable.
17. When you squeeze an air-filled party balloon, you increase its
(a) volume.
(b) mass.
(c) weight.
(d) density.
18. In a hydraulic press operation, the output piston cannot
(a) move farther than the input piston.
(b) exceed the force input.
(c) exceed the input piston's speed.
(d) produce increased energy.
19. The flight of a blimp best illustrates
(a) Archimedes' principle.
(b) Pascal's principle.
(c) Bernoulli's principle.
(d) Boyle's law.
20. When wind speeds up as it blows over the top of a hill, atmospheric pressure there
(a) increases.
(b) decreases.
(c) isn't affected.
(d) reduces to zero.

After you have made thoughtful choices, and discussed them with your friends, find the answers on page S-1.