14 Gases

Photo openers begin with the father-and-son team of physics professors, P.O. and Johan Zetterberg, pulling on a classroom model of the Magdeburg hemispheres. Photo 2 is a depiction of the original experiment by Otto von Guericke. Photos 3 and 4 are physics friend Evan Jones, demonstrating his favorite physics activity, the Bernoulli Principle. Norwegian physics friend Ole Anton Haugland conducts atmospheric research in photo 5.

The personal profile is of dear Swedish friends, the Zetterbergs and Sara Blomberg.

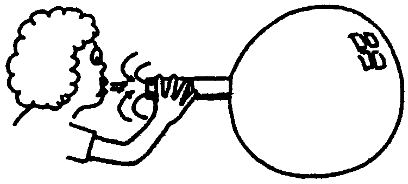
The concepts of fluid pressure, buoyancy, and flotation introduced in the previous chapter are applied to the atmosphere in this chapter. The chief difference between common fluid water and common fluid air has to do with the variability of density. Unlike a body of water, the density of the atmosphere is depth-dependent. The section on Boyle's Law avoids distinguishing between absolute pressure and gauge pressure. Charles' Law is not covered, and reference is made to temperature effects only in a footnote.

The ideal gas law in the form $PV = nRT$, especially in chemistry classes, where n is the number of moles of gas (one mole is equal to 6.02×10^{23} particles). The quantity R is a number called the *molar* (universal) *gas constant* and has a value of 8.31 J/(mol·K). Treatment of Boyle's law in this chapter is much simpler.

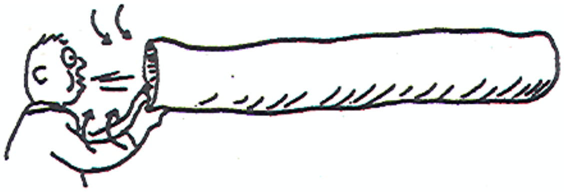
The first three phases of matter, solids, liquids, and gases, are well known. The fourth phase, plasma, is less well known. It is widely known in its role in TV sets and nuclear fusion research.

If you're into lecture demonstrations, this is the chapter material for a show. There are two good sources I have found useful: *A Demonstration Handbook for Physics*, by G.D. Frier and F.J. Anderson, published by AAPT, and *Invitations to Science Inquiry*, by the late Tik L. Liem, at St. Francis Xavier University, in Antigonish, Nova Scotia.

Blowing bubbles is always fun, and here's one from the Exploratorium that nicely illustrates Bernoulli's Principle. Question: Can you blow a 1-breath bubble bigger than your lungs? Answer: Yes, depending on how you do it. Here's how: Tape together two or three small juice cans that have had both ends removed. (You can use the cardboard core of a roll of paper towels, but this tube will not last through repeated uses.) Make up a soap solution that consists of concentrated Joy or Dawn dish liquid, glycerin, and water [recipe: 1 gallon of water, $^{2}/_{3}$ cup of dishwashing soap, 3 tablespoonfuls glycerin (available from any drugstore)]. Let the solution stand overnight, for better bubbles are produced by an "aged" mixture. Dip the tube to form a soap film over the end. To make a lung-sized bubble, take a deep breath and, with your mouth near but not touching the nonsoapy end of the tube, exhale and blow a bubble. Don't blow too hard or else the bubble film will break. You'll note the size of this bubble is nearly the volume of your lungs (you can't exhale *all* the air from your lungs).



You can do the same with a long plastic bag. Invite students to blow up the bag, counting their breaths. After two or three students have demonstrated that many breaths of air are required, announce that you can do it with one breath. Then hold the bag a few centimeters in front of your mouth, not on it as your students likely did, and then blow. Air pressure in the airstream you produce is reduced, entrapping surrounding air to join in filling up the bag! (Available from Arbor Scientific. P6-7350.)



The text credits Bernoulli's principle and the airfoil shape of wings to explain wing lift, but wings would work without the airfoil. Remember those model planes you flew as a kid, that were constructed of flat wings? And do you remember that the slot to hold the wing was cut with an "angle of attack"? In this way, oncoming air is forced downward. Newton's 3rd law states the rest: If the wing forces air downward, the air simultaneously forces the wing upward. So birds were able to fly before the time of Daniel Bernoulli. The question is sometimes raised; could birds fly before the time of Isaac Newton?

I've found only futility in trying to explain Bernoulli's principle in terms of differences in molecular impacts on the top and bottom surfaces of wings. Especially when experiments show that molecules don't make impact upon the top surface anyway. A thin boundary layer of air is carried in this low-pressure region as evidenced by the dust found on the surface of fan blades!

In distinguishing between laminar and turbulent flow: Blood flow in the arteries is normally laminar, but when arteries are clogged, blood flow becomes turbulent and the heart has to work harder, resulting in higher blood pressure and a variety of other medical complications. Laminar airflow from hand dryers in public restrooms takes a longer drying time. Turbulent airflow does a better job of drying in a shorter time. Interestingly, you approximate turbulent airflow when you shake your hand in the airflow.

In discussing the global atmosphere, if you get into the abuses that the atmosphere is undergoing, acid rain, and so on, please do not end on a sour note. Also get into what can be done to better the situation. Our students have no shortage of inputs telling them about the abuses of technology, and they hear less often about how technology can be used to improve the quality of life in the world.

Practicing Physics Book:
- Gas Pressure

Problem Solving Book:
There are many problems on gases and atmospheric pressure

Laboratory Manual:
- Tire Pressure and 18-Wheelers Force, Area, and Pressure (Experiment)

Next-Time Questions include:
- Empty Refrigerator
- Flexible Bottle
- Bell Jar
- Floating Ping-Pong Ball
- Weighted Balloon
- Balloon in Falling Elevator
- Balsa Wood and Iron
- Inverted Glass
- Whirling Candle
- Space Shuttle Candle
- Bernoulli Top
- Two Balloons

Hewitt-Drew-It! Screencasts: •*Atmospheric Pressure* •*Boyle's Law* •*Buoyancy of Balloons* •*Air-Buoyancy Problems* •*Bernoulli Principle* •*Bernoulli Applications*

This chapter is not prerequisite to the following chapters.

SUGGESTED LECTURE PRESENTATION

Weight of Air

Hold out an empty drinking glass and ask what's in it. It's not really empty, for it's filled with air, and has weight. It is common to think of air as having very little mass, when the truth is air has a fairly large mass—about $1\frac{1}{4}$ kilogram for a cube one meter on a side (at sea level). The air that fills your bathtub has a mass of about $\frac{1}{2}$ kilogram. We don't feel the weight of this mass only because we are immersed in an ocean of air. A plastic bag full of water, for example, has a significant weight, but if the bag is taken into a swimming pool it weighs nothing (Figure 14.3). Likewise for the surrounding air. A bag of air may have a fairly large mass, but as long as the bag is surrounded by air, its weight is not felt. We are as unconscious of the weight of air that surrounds us as a fish is unconscious of the weight of water that surrounds it.

> CHECK QUESTION: Open the door of a refrigerator and inside is a large lonely grapefruit. Which weighs more, the air in the fridge or the grapefruit? [The inside volume of a common refrigerator is between $\frac{1}{2}$ and $\frac{3}{4}$ m^3, which corresponds to nearly a kilogram of cold air (about 2 pounds). So unless the grapefruit is more than a 2-pounder, the air weighs more.]

The Atmosphere

Draw a circle as large as possible on the chalkboard, and then announce that it represents the Earth. State that if you were to draw another circle, indicating the thickness of the atmosphere surrounding the Earth to scale, you would be drawing the same line—for over 99% of the atmosphere lies within the thickness of the chalk line! Then go on to discuss the ocean of air in which we live.

> DEMONSTRATION: While discussing the preceding, have a gallon metal can with a bit of water in it heating on a burner. When steam issues, cap it tightly and remove from the heat source. Continue your discussion and the collapsing can will interrupt you as it crunches. If you really want to impress your class, do the same with a 50-gallon drum! [The explanation is that pressure inside the can or drum decreases as cooling occurs and the steam condenses. Atmospheric pressure on the outside produces the crunching net force on the can or drum.] (These demos are featured in the photo openers of Chapter 18.)
>
> DEMONSTRATION: You may or may not want to get into the dramatic demo of crunching soda-pop cans by atmospheric pressure. This is featured in the thermodynamics chapter, page 348. Since it features condensation, perhaps better to treat it later. But for an impressive demo of atmospheric pressure, it complements the collapsing 50-gallon drum!

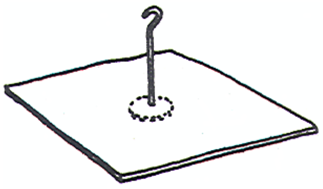
Atmospheric Pressure

While this is going on, state that if you had a 30-km tall bamboo pole of cross section 1 square cm, the mass of the air from the atmosphere in it would amount to about 1 kg. The weight of this air is the source of atmospheric pressure. The atmosphere bears down on the Earth's surface at sea level with a pressure that corresponds to the weight of 1 kg per square cm. (Some of you may remember the old days when we could talk about plain old 14.7 $1b/in^2$. Since the unit of force is now the newton and the unit of area is the square meter, conceptualizing atmospheric pressure is less simple than before. Nevertheless, continue with the following description.) To understand the pressure of the atmosphere in terms of newton per square meter, ask your class to imagine a 30-km tall sewer pipe of cross section 1 square m, filled with the air of the atmosphere. How much would the enclosed air weigh? The answer is about 10^5 N. So if you draw a circle of one square meter on the lecture table, and ask what the weight is for all the air in the atmosphere above, you should elicit a chorus, silent or otherwise of "10^5 N!" If your table is above sea level, then the weight of air is correspondingly less. Then estimate the force of the air pressure that collapsed the metal can—both of a perfect vacuum and for a case where the pressure difference is about half an atmosphere.

Paul Doherty at the Exploratorium has a steel bar 1.31 m long that has a cross-sectional area of one square inch. It weighs 14.7 pounds. When balanced vertically it produces 14.7-lb/in^2 pressure—that of the atmosphere. Problems with this approach for the atmospheres of other planets are nicely featured in the Problem Solving Book.

Estimate the force of the atmosphere on a person. You can estimate the surface area by approximating different parts of the body on the board—leg by leg, arm by arm, etc. (This can be quite funny, if you want it to be!)

> DEMONSTRATION: This great one from John McDonald of Boise State University in Idaho that consists of a square sheet of soft rubber with some sort of handle at its center. A 50-gram mass hanger poked through its center works well. Toss the rubber sheet on any perfectly flat surface—best on the top of a lab stool. Picking the rubber up by a corner is an easy task because the air gets under it as it is lifted. But lifting it by the middle is another story. As the middle is raised, a low-pressure region is formed because air cannot get in. The rubber sheet behaves as a suction cup, and the entire stool is lifted when the handle is raised. (A version of this is available from Arbor Scientific. P1-2010.)



> DEMONSTRATION: Whap a toilet plunger or other suction cup on the wall. (Instruct your class to inquire with their neighbors to see if there is a consensus as to the reason.)

> DEMONSTRATION: Place a wooden shingle on the lecture table so that it overhangs the edge a bit. Cover the shingle with a flattened sheet of newspaper, and strike the overhanging part of the shingle with a stick or your hand (be careful of splinters). Promote more "discuss with your neighbor" activity.

Discuss the cushion of air provided by the wonderful air puck demonstrated by Ann Brandon in Figure 14.6. The puck she demonstrates was made by her students as a class project. Can you do the same?

Barometer

State that a better vacuum source than sucking would remove much more air, and if all the air were removed, a very large column of water would be needed to balance the atmosphere on the other side. This would be about 10.3 m, but depends a little on today's atmospheric pressure. Such devices made up the first barometers. They are impractically large, so mercury is instead commonly used. Since mercury is 13.6 times as dense as water, the height of water needed to balance the atmosphere is $^{1}/_{13.6}$ of 10.3 m = 76 cm. If you have the opportunity, construct a mercury barometer before the class.

> CHECK QUESTION: How would the barometer level vary while ascending and descending in the elevator of a tall building? [You might quip about the student who was asked to find the height of a building with a sensitive barometer who simply dropped it from the top and measured the seconds of fall—or who exchanged it with the builder of the building for the correct information.]

Discuss ear popping in aircraft, and why cabin pressure is lower than atmospheric pressure at high altitudes.

> DEMONSTRATION: As the sketch shows, try sucking a drink through a straw with two straws; one in the liquid and the other outside. It can't be done because the pressure in your mouth is not reduced because of the second straw (although with some effort a bit of liquid can be drawn). Invite your students to try this, and to share this (and other ideas!) at parties.

> DEMONSTRATION: The siphon. Careful! Many instructors have found in front of their classes that they misunderstood the operation of a siphon. The explanation does not have to do with differences in atmospheric pressures at the ends of the tube, but with the end of the tube exceeds 10.3 m, atmospheric pressure acting upwards against the liquid in the tube is greater than the downward pressure of liquid. The situation is analogous to

> pushing upward against the bottom ends of a seesaw with unequal pushes. Liquid in the short end of the tube is pushed up with more net force than the liquid in the long end of the tube. (Or it's analogous to a chain hanging over a peg, with one end longer and heavier than the other end.)

Boyle's Law

Discuss Boyle's Law. At the risk of information overload you may or may not want to get into the differences between absolute and gauge pressures. (I avoid it in the text.)

Consider discussion of Think and Do 31, estimating the weight of a car by the pressure in its tires and the amount of tire contact area. Now your students know why trailer trucks commonly have 18 wheels—the air pressure in the tires multiplied by the area of contact of the 18 tires is the weight of the truck and its load. Fewer tires mean greater air pressure in the tires. (In this project we ignore the significant support supplied by the sidewalls of the tires—much more in today's tires.)

Discuss or show Think and Do 32 (dunking a glass mouth downwards in water to show the "empty" glass contains air—and how air is compressed with deeper depths) and relate this to the compressed air breathed by scuba divers. Discuss the reason for the difficulty of snorkeling at a depth of 1 m and why such will not work for greater depths; i.e., air will not of itself move from a region of lesser pressure (the air at the surface) to a region of greater pressure (the compressed air in the submerged person's lungs).

Recall the sinking balloon problem from the previous chapter (Think and Discuss 39 in Chapter 13) and relate this to the smaller volume to which a swimmer is subjected with increasing depth. Hence the need for pressurized air for scuba divers. Without the pressurized air, one's volume and therefore buoyancy is decreased, making it more difficult to return to the surface. Whereas at shallow depths the average swimmer can passively return to the surface, at greater depths a passive swimmer will sink to the bottom.

Buoyancy of Air

Hold your hands out, one a few centimeters above the other, and ask if there really is any difference in air pressure at the two places. The fact that there is can be demonstrated by the rising of a helium-filled balloon of the same size! The balloon rises only because the atmospheric pressure at its bottom is greater than the atmospheric pressure at its top. Pressure in the atmosphere really is depth-dependent!

> CHECK QUESTION: Which is greater, the buoyant force on the helium-filled balloon, or the buoyant force on you? [Assuming the balloon has less volume than you, there is more buoyant force on you.] Discuss why.

Interestingly enough, atmospheric pressure halves with every 6 km increase in elevation, so a freely expanding balloon grows by twice its volume with each 6 km rise. Does this increase the buoyant force? No, because the displacement of twice as much half-as-dense air has the same weight!

> CHECK QUESTION: A large block of Styrofoam and a small block of iron have identical weights on a weighing scale. Which has the greater mass? [Actually the Styrofoam has the greater mass. This is because it has a greater volume, displaces more air, and experiences a great buoyant force. So it's weight on the scale is its "true weight," minus the buoyant force of the air, which is the case for all things weighed in air. The fact that it reads the same on the scale as the iron means it must have more mass than the iron. (A lobster that walks on a bathroom scale on the ocean bottom has more mass than the reading indicates.)]

> CHECK QUESTIONS: What would happen to the bubbles in a beer mug if you dropped the mug of beer from the top of a high building? Would the bubbles rise to the top, go to the bottom, or remain motionless with respect to the mug? [First of all, you'd likely be apprehended for irresponsible behavior. As for the bubbles, they'd remain motionless relative to the mug, since the local effects of gravity on the beer would be absent. This is similar to the popular demo of dropping a cup of water with holes in the side. When held at rest the water spurts out, but drop it and the spurting stops.]

Bernoulli's Principle

Introduce Bernoulli's principle by blowing into a spool as Evan Jones does in the opening photos of the chapter. A piece of card at the opposite end isn't blown off! Follow up with a variety of demonstrations as suggested:

> DEMONSTRATIONS:
> (1) Make a beach ball hover in a stream of air issuing from the reverse end of a vacuum cleaner.
> (2) Do the same with a Ping-Pong ball in the airstream of a hairdryer.
> (3) Line a cardboard tube with sandpaper and sling the ball sidearm. The sandpaper produces the friction to make the ball roll down the tube and emerge spinning—you'll see that the ball breaks in the correct direction. Point out that paddles have a rough surface like the sandpaper for the same reason—to spin the ball when it is properly struck—that is, to apply "English" to the ball.
> (4) Swing a Ping-Pong ball taped to a string into a stream of water as shown. Follow this up with a discussion of the shower curtain in the last paragraph of Bernoulli's Principle.

> DEMONSTRATION: Place a pair of upright empty aluminum soft drink cans on a few parallel straws on your lecture table. Blow between the cans and they roll toward each other. Or do the same with the nearby cans suspended by strings. A puff of air between them makes them click against one another, rather than blowing them apart as might be expected. [Some people avoid Bernoulli's principle because in some cases, like plane flight, there are alternate models to account for the forces that occur. These clicking cans, however, are straight Bernoulli!]

> DEMONSTRATION: Show the sailboat demo described earlier for Chapter 5 in this manual; first with the flat sail, and then with the curved sail. The difference is appreciable. It's nice if you can show this on an air track.

Plasma

Describe the changes of phase of matter as the rate of molecular motion is increased in a substance, say piece of ice changing to water, and then to steam. State how increased motion results in the molecules shaking apart into their constituent atoms, and how still increased motion results in the freeing of orbital electrons from the atomic nuclei—and you have a plasma. Acknowledge the partial plasmas in the everyday world—advertising signs, fluorescent lamps, street lamps, and the like. Discuss the role of plasma in power production (MHD generators, Chapter 25).

Discuss the role of plasma in TV sets. A search on the web will provide you with detailed explanations.

> NEXT-TIME QUESTION: Place a small birthday-type candle in a deep drinking glass. When the glass is whirled around in a circular path, say held at arm's length while one is spinning like an ice skater, which way does the flame point? And most important, why? (Note the similarity of this with Think and Explain 66.)

> NEXT-TIME QUESTION: Discuss the role of Bernoulli in increasing the size of wave in the wind. [Air pressure is reduced as air increases speed in moving over the tops of waves, and increased in the troughs. This pressure difference enhances the height of the waves.]

Answers and Solutions to Chapter 14

Reading Check Questions

1. The Sun is the energy source for motion of air molecules. Earth's gravity pulls air molecules down, keeping most from escaping into space.
2. Half the atmosphere is below 5.6 kilometers.
3. The cause of atmospheric pressure is the weight of air.
4. The mass of one cubic meter of air is about 1.25 kg.
5. Approximate mass is 1 kg, with weight 10 N.
6. Pressure is 10 N/cm^2.
7. Both pressures are the same.
8. Both weights are the same.
9. It would have to be taller because it's 1/13.6 as dense.
10. Correct to say pushed up. The pressure of the surrounding air does the pushing.
11. The atmosphere can push water a maximum of 10.3 m via its pressure.
12. The pressure sensed by an aneroid barometer is calibrated in altitude.
13. Density doubles when volume is halved.
14. Pressure doubles when volume is halved.
15. An ideal gas is one in which intermolecular forces and size of molecules can be neglected.
16. BF equals 1 N. If the BF decreases, the balloon descends. If BF increases, the balloon ascends.
17. A BF exists for all objects that displace fluid.
18. The balloons expand and would likely rupture with increased altitude if fully inflated.
19. Streamlines are imaginary lines that show the path of a fluid.
20. Where streamlines are crowded, pressure is less.
21. When speed increases, internal pressure decreases.
22. When speed decreases, internal pressure increases.
23. Bernoulli's principle is about internal pressures.
24. Faster-moving air above the wing has reduced pressure.
25. Faster-moving water between the ships results in reduced pressure.
26. The ships are pushed together by the greater water pressure on their opposite sides.
27. The fluid is pushed up by the pressure of the atmosphere on its surface.
28. Particles in a gas are electrically neutral. In a plasma they're charged.
29. Neon signs, fluorescent lamps, certain TV screens.
30. Low pollution MHD power can be produced when a plasma beam is directed into the field of a magnet

Think and Do

31. The pressures should be approximately the same. The rigid walls of the tire prevent the pressure calculations from being closer. The calculated value should therefore be somewhat greater.

32. This is certainly worth doing!

33. You have a barometer of sorts, but since the medium is water, it would have to reach a column 10.3 m tall to give the same pressure as a column of mercury 76 cm tall.

34. Atmospheric pressure holds the card to the glass, in any direction.

35. The gurgling is due to air entering the jar. No gurgling would occur if this were somehow tried on the Moon where there is no atmosphere.

36. The aluminum can implodes dramatically. What occurs is rapid condensation of the steam, described later in Chapter 18. This is a must-do activity!

37. When your finger closes the top of the water-filled straw, atmospheric pressure no longer acts on the top part of the water, which is easily lifted. When you raise your finger the water spills out the bottom. This is a nice procedure for transferring liquids from one test tube to another.

38. The blown air that spreads between the spool and card is of low pressure, low enough that the greater atmospheric pressure on the outside part of the card presses the card to the spool.

39. Water pressure is lowered in the part flowing over the curved part of the spoon, resulting in that part moving toward the stream instead of away from it.

Think and Solve

40. To find the buoyant force that the air exerts on you, find your volume and multiply by the weight density of air (From Table 14.1 we see that the mass of 1 m^3 of air is about 1.25 kg. Multiply this by 10 N/kg and you get 12.5 N/m^3). You can estimate your volume by your weight and by assuming your density is approximately equal to that of water (a little less if you can float). The weight density of water is 10^4 N/m^3, which we'll assume is your density. By ratio and proportion:

$$= \frac{\text{(your weight in newtons)}}{\text{(your volume in meters}^3\text{)}} .$$

If your weight is a heavy 1000 N, for example (about 220 lb), your volume is 0.1 m^3. So buoyant force = 12.25 $N/m^3 \times$ 0.1 m^3 = about 1.2 N, roughly the weight of an apple. (A useful conversion factor is 4.45 N = 1 pound.) Another way to do this is to say that the ratio of the buoyant force to your weight is the same as the ratio of air density to water density (which is your density). This ratio is 1.25/1000 = 0.00125. Multiply this ratio by your weight to get the buoyant force.

41. To effectively lift (0.25)(80 kg) = 20 kg the mass of displaced air would be 20 kg. Density of air is about 1.2 kg/m^3. From density = mass/volume, the volume of 20 kg of air, also the volume of the balloon (neglecting the mass of the helium) would be volume = mass/density = (20 kg)/(1.2 kg/m^3) = **17 m^3**. (Of course as altitude is reached the helium in the balloon expands, displacing more volume of air – but thinner air as the atmosphere also becomes less dense.)

42. (a) The weight of the displaced air must be the same as the weight supported, since the total force (gravity plus buoyancy) is zero. The displaced air weighs **20,000 N**.
(b) Since weight = mg, the mass of the displaced air is $m = W/g$ = (20,000 N)/(10 m/s^2) = 2,000 kg. Since density is mass/volume, the volume of the displaced air is volume = mass/density = (2,000 kg)/(1.2 kg/m^3) = **1,700** m^3 (same answer to two figures if $g = 9.8\ m/s^2$ is used).

43. From $P = \frac{F}{A}$; $F = PA = (0.04)\left(10^5 \frac{N}{m^2}\right)(100\ m^2) = 4 \times 10^5$ N .

44. From $P = F/A$ = (den $\times g \times$ vol)/A = (den $\times g \times A \times h$)/A = den $\times g \times h$; $h = P/(\text{den} \times g)$ = (100,000 N/m^2)/(1.2 $kg/m^3 \times$ 10 N/kg) = 8300 m = 8.3 km.

Think and Rank

45. A, B, C
46. A, C, B
47. C, A, B

Think and Explain

48. Some of the molecules in the Earth's atmosphere *do* go off into outer space—those like helium with speeds greater than escape speed. But the average speeds of most molecules in the atmosphere are well below escape speed, so the atmosphere is held to Earth by Earth's gravity.

49. There is no atmosphere on the Moon because the speed of a sizable fraction of gas molecules at ordinary temperatures exceeds lunar escape velocity (because of the Moon's smaller gravity). Any appreciable amounts of gas have long leaked away, leaving the Moon airless.

50. The tires heat, giving additional motion to the gas molecules within.

51. When the diameter is doubled, the area is four times as much. For the same pressure, this would mean four times as much force.

52. At higher altitude, less atmospheric pressure is exerted on the ball's exterior, making relative pressure within greater, resulting in a firmer ball.

53. The ridges near the base of the funnel allow air to escape from a container it is inserted into. Without the ridges, air in the container would be compressed and would tend to prevent filling as the level of liquid rises.

54. The density of air in a deep mine is greater than at the surface. The air filling up the mine adds weight and pressure at the bottom of the mine, and according to Boyle's law, greater pressure in a gas means greater density.

55. The bubble's mass does not change. Its volume increases because its pressure decreases (Boyle's law), and its density decreases (same mass, more volume).

56. Airplane windows are small because the pressure difference between the inside and outside surfaces result in large net forces that are directly proportional to the window's surface area. (Larger windows would have to be proportionately thicker to withstand the greater net force—windows on underwater research vessels are similarly small.)

57. Unlike water, air is easily compressed. In fact, its density is proportional to its pressure (at a given temperature). So, near the ground, where the pressure is greater, the air's density is greater and corresponds to more squashed bricks; at high altitude, where the pressure is less, the air's density is less, corresponding to less squashed bricks.

58. A vacuum cleaner wouldn't work on the Moon. A vacuum cleaner operates on Earth because the atmospheric pressure pushes dust into the machine's region of reduced pressure. On the Moon there is no atmospheric pressure to push the dust anywhere.

59. A perfect vacuum pump could pump water no higher than 10.3 m. This is because the atmospheric pressure that pushes the water up the tube weighs as much as 10.3 vertical meters of water of the same cross-sectional area.

60. If barometer liquid were half as dense as mercury, then to weigh as much, a column twice as high would be required. A barometer using such liquid would therefore have to be twice the height of a standard mercury barometer, or about 152 cm instead of 76 cm.

61. The height of the column in a mercury barometer is determined by pressure, not force. Fluid pressures depend on density and depth—pressure at the bottom of a wide column of mercury is no different than at the bottom of a narrow column of mercury of the same depth. The weight of fluid *per area* of contact is the same for each. Also with the surrounding air, hence why wide and narrow-tube barometers show the same height.

62. Mercury can be drawn a maximum of 76 cm with a siphon. This is because 76 vertical cm of mercury exert the same pressure as a column of air that extends to the top of the atmosphere. Or looked at another way; water can be lifted 10.3 m by atmospheric pressure. Mercury is 13.6 times denser than water, so it can only be lifted only $^{1}/13.6$ times as high as water.

63. The height would be less. The weight of the column balances the weight of an equal-area column of air. The denser liquid would need less height to have the same weight as the mercury column.

64. Drinking through a straw is slightly more difficult atop a mountain. This is because the reduced atmospheric pressure is less effective in pushing soda up into the straw.

65. One's lungs, like an inflated balloon, are compressed when submerged in water, and the air within is compressed. Air will not of itself flow from a region of low pressure into a region of higher pressure. The diaphragm in one's body reduces lung pressure to permit breathing, but this limit is strained when nearly 1 m below the water surface. This limit is exceeded at more than a depth of 1 m.

66. The air tends to pitch toward the rear (law of inertia), becoming momentarily denser at the rear of the car, less dense in the front. Because the air is a gas obeying Boyle's law, its pressure is greater where its density is greater. Then the air has both a vertical and a horizontal "pressure gradient." The vertical gradient, arising from the weight of the atmosphere, buoys the balloon up. The horizontal gradient, arising from the acceleration, buoys the balloon forward. So the string of the balloon makes an angle. The pitch of the balloon will always be in the direction of the acceleration. Step on the brakes and the balloon pitches backwards. Round a corner and the balloon noticeably leans radially towards the center of the curve. Nice! (Another way to look at this involves the effect of two accelerations, *g* and the acceleration of the car. The string of the balloon will be parallel to the resultant of these two accelerations. Nice again!)

67. The lead and feathers have the same mass. Weight is measured as the force with which something presses on a supporting surface. When the buoyancy of air plays a role, the net force against the supporting surface is less, indicating a smaller weight. Buoyant force is more appreciable for larger volumes, like feathers. So with less buoyancy, the same mass of lead weighs more than the same mass of feathers.

68. Objects that displace air are buoyed upward by a force equal to the weight of air displaced. Objects therefore weigh less in air than in a vacuum. For objects of low densities, like bags of compressed gases, this can be important. For high-density objects like rocks and boulders the difference is usually negligible.

69. Helium is less dense than air, and will weigh less than an equal volume of air. A helium-filled bottle would weigh less than the air bottle (assuming they are filled to the same pressure). However, the helium-filled bottle will weigh more than the empty bottle.

70. The buoyant force does not change, because the volume of the balloon does not change. The buoyant force is the weight of air displaced, and doesn't depend on what is doing the displacing. The net lift, however, is greater because of a smaller weight of gas.

71. An object rises in air only when buoyant force exceeds its weight. A steel tank of anything weighs more than the air it displaces, so won't rise. Also, the helium is compressed in the tank, and wouldn't rise even if the tank's weight were nil. A helium-filled balloon weighs less than the air it displaces and rises.

72. A moving molecule encountering a surface imparts force to the surface. The greater the number of impacts on a given-size surface, the greater the pressure.

73. According to Boyle's law, the pressure will increase to **three times** its original pressure.

74. The volume of gas in the balloon increases.

75. The pressure increases, in accord with Boyle's law.

76. Pressure of the water decreases and the bubbles expand.

77. The shape would be a catenary. It would be akin to Gateway Arch in St. Louis and the hanging chain discussed in Chapter 12.

78. The stretched rubber of an inflated balloon provides an inward pressure. So the pressure inside is balanced by the sum of two pressures; the outside air pressure plus the pressure of the stretched balloon. (The fact that air pressure is greater inside an inflated balloon than outside is evident when it is punctured—the air "explodes" outward.)

79. The force of the atmosphere is on both sides of the window; the net force is zero, so windows don't normally break under the weight of the atmosphere. In a strong wind, however, pressure will be reduced on the windward side (Bernoulli's Principle) and the forces no longer cancel to zero. Many windows are blown *outward* in strong winds.

80. According to Bernoulli's principle, the wind at the top of the chimney lowers the pressure there, producing a better "draw" in the fireplace below.

81. As speed of water increases, internal pressure within the water decreases.

82. Air speed across the wing surfaces, necessary for flight, is greater when facing the wind.

83. Air moves faster over the spinning top of the Frisbee and pressure against the top is reduced. A Frisbee, like a wing, needs an "angle of attack" to ensure that the air flowing over it follows a longer path than the air flowing under it. So there is a difference in pressures against the top and bottom of the Frisbee that produces an upward lift.

84. (a) Speed increases (so that the same quantity of gas can move through the pipe in the same time). (b) Pressure decreases (Bernoulli's principle). (c) The spacing between the streamlines decreases, because the same number of streamlines fit in a smaller area.

85. Spacing of airstreams on opposite sides of a non-spinning ball are the same. For a spinning ball, airstream spacings are less on the side where airspeed is increased by spin action.

86. A tennis ball has about the same size as a baseball, but much less mass. Less mass means less inertia, and more acceleration for the same force. A Ping-Pong ball provides a more obvious curve due to spinning because of its low mass.

87. Greater wing area produces greater lift, important for low speeds where lift otherwise would be less. Flaps are pulled in to reduce area at cruising speed, where a smaller wing area can provide lift equal to the weight of the aircraft.

88. An airplane flies upside down by tilting its fuselage so that there is an angle of attack of the wing with oncoming air. (It does the same when flying right side up, but then, because the wings are designed for right-side-up flight, the tilt of the fuselage may not need to be as great.)

89. The thinner air at high-altitude airports produces less lift for aircraft. This means aircraft need longer runways to achieve greater speed for takeoff.

90. In accord with Bernoulli's principle, the sheets of paper will move together because air pressure between them is reduced, and be less than the air pressure on the outside surfaces.

91. Bernoulli's Principle. For the moving car the pressure will be less on the side of the car where the air is moving fastest—the side nearest the truck, resulting in the car's being pushed by the atmosphere towards the truck. Inside the convertible, atmospheric pressure is greater than outside, and the canvas rooftop is pushed upwards towards the region of less pressure. Similarly for the train windows, where the interior air is at rest relative to the window and the air outside is in motion. Air pressure against the inner surface of the window is greater than the atmospheric pressure outside. When the difference in pressures is great enough, the window is blown out.

92. A solid-walled wharf is disadvantageous to ships pulling alongside because water currents are constrained and speed up between the ship and the wharf. This results in a reduced water pressure, and the normal pressure on the other side of the ship then forces the ship against the wharf. The pilings avoid this mishap by allowing the freer passage of water between the wharf and the ship.

Think and Discuss

93. The weight of a truck is distributed over the part of the tires that make contact with the road. Weight/surface area = pressure, so the greater the surface area, or equivalently, the greater the number of tires, the greater the weight of the truck can be for a given pressure. What pressure? The pressure exerted by the tires on the road, which is determined by (but is somewhat greater than) the air pressure in its tires. Can you see how this relates to Think and Do 31?

94. To begin with, the two teams of horses used in the Magdeburg hemispheres demonstration were for showmanship and effect, for a single team and a strong tree would have provided the same force on the hemispheres. So if two teams of nine horses each could pull the hemispheres apart, a single team of nine horses could also, if a tree or some other strong object were used to hold the other end of the rope.

95. If the item is sealed in an air-tight package at sea level, then the pressure in the package is about 1 atmosphere. Cabin pressure is reduced somewhat for high altitude flying, so the pressure in the package is greater than the surrounding pressure and the package therefore puffs outwards.

96. If an elephant steps on you, the pressure that the elephant exerts is over and above the atmospheric pressure that already is exerted on you. It is the *extra* pressure the elephant's foot produces that crushes you. For example, if atmospheric pressure the size of an elephant's foot were somehow removed from a patch of your body, you would be in serious trouble. You would be soothed, however, if an elephant stepped onto this area!

97. You agree with your friend, for the elephant displaces far more air than a small helium-filled balloon, or small anything. The *effects* of the buoyant forces, however, is a different story. The large buoyant force on the elephant is insignificant relative to its enormous weight. Not so for the tiny buoyant force acting on the balloon of tiny weight.

98. If the air pressure in the inflated balloon were equal to the outside air pressure, the extra weight of the air in the balloon would be canceled by an equal buoyant force and the scale reading would not change. But to keep a rubber balloon inflated, its air pressure inside has to be greater than outside air pressure. Then the extra weight is greater than the buoyant force and the scale will show a greater weight.

99. No, assuming the air is not compressed. The air filled bag is heavier, but buoyancy negates the extra weight and the reading is the same. The buoyant force equals the weight of the displaced air, which is the same as the weight of the air inside the bag (if the pressures are the same).

100. The end supporting the punctured balloon tips upwards as it is lightened by the amount of air that escapes. There is also a loss of buoyant force on the punctured balloon, but that loss of upward force is less than the loss of downward force, since the density of air in the balloon before puncturing was greater than the density of surrounding air.

101. The balloon which is free to expand will displace more air as it rises than the rigid balloon. Hence, the balloon that is free to expand will experience more buoyant force than the balloon that does not expand, and will rise higher. Also, as the rigid balloon rises, its constant volume displaces ever-lighter volumes of air.

102. The buoyant force on each is the same, but is much less effective for the basketball due to its greater weight. Buoyancy is simply more conspicuous on the helium-filled balloon.

103. The rotating habitat is a centrifuge, and denser air is “thrown to” the outer wall. Just as on Earth, the maximum air density is at “ground level,” and becomes less with increasing altitude (distance toward the center). Air density in the rotating habitat is least at the zero-*g* region, the hub.

104. The helium-filled balloon will be buoyed from regions of greater pressure to regions of lesser pressure, and will “rise” in a rotating air-filled habitat.

105. According to Bernoulli’s principle, when a fluid gains speed in flowing through a narrow region, the pressure of the fluid is reduced. The gain in speed, the cause, produces reduced pressure, the effect. But one can argue that a reduced pressure in a fluid, the cause, will produce a flow in the direction of the reduced pressure, the effect. For example, if you decrease the air pressure in a pipe by a pump or by any means, neighboring air will rush into the region of reduced pressure. In this case the increase in air speed is the result, not the cause of, reduced pressure. Cause and effect are open to interpretation. Bernoulli’s principle is a controversial topic with many physics types!