10

Properties of Matter

KEY IDEA

Properties of a material depend on the way in which its atoms are put together.

PHYSICS AROUND US . . . Giant Animals

Sometimes it's fun to watch old science fiction movies. You know the kind we mean, the ones in which giant grasshoppers attack Chicago, or Tokyo is menaced by a new kind of monster. In these old films, before computer technology made possible the construction of truly frightening monsters, the director's choices were either to make models of dinosaurs and giant gorillas or to scale up other sorts of animals—ants, for example, or spiders.

But could an ant with six skinny legs really become 20 feet tall? Could its outer skeleton support all that extra weight? Ever since Galileo's work in the seventeenth century on the properties of materials, scientists have known that the answer is no.

Today, this bit of scientific lore is well established among movie makers, and the old-fashioned, impossible monsters are seldom seen. That shouldn't stop you from enjoying the old movies, however.

OUR MATERIAL WORLD

Humans value different materials because of their diverse useful properties. Strong superglue, shatterproof glass, colorful dyes, resilient plastics, long-lasting paints, lightweight alloys, soft fabrics, flexible wire, efficient insulation, safe preservatives, effective drugs—the list goes on and on. Why do different materials show such an amazing range of properties?

Many of the everyday properties of materials can be understood if we think about the behavior of the atoms from which they are built. Conversely, once we understand how different kinds of atoms behave under various conditions, we can design materials that have the properties we're looking for. The list of materials in the previous paragraph contains only synthetic products; the ability to manufacture these substances springs from an understanding of how atoms interact. (See Physics and Modern Technology on page 205.) In many respects, understanding the interplay of atomic behavior and the resulting properties of matter has completely changed the modern world. Many of the devices common today but unheard of 50 years ago (lasers, computers, spacecraft, cell phones, credit cards) would not have been possible without advances in semiconductors, plastics, and metal alloys—the materials of the new age.

In this chapter we examine three familiar material properties: the density of materials, their response to pressure, and their elasticity. We encounter these properties every day in countless ways. We shall see that behaviors as diverse as floating in water, keeping aircraft in the air, and constructing buildings that don't fall down are all related to atoms and the way they interact with one another.

DENSITY

Pick up a brick and a piece of wood of the same size and you'll immediately notice that the brick is heavier. There are two reasons for this difference. First, the atoms in the brick include species such as potassium and silicon, which are more massive than the carbon and oxygen atoms that make up most of the wood. Second, the arrangement of atoms is such that the atoms in the brick are, on average, packed more closely together than the atoms in the wood. As a consequence, the brick weighs more than the wood, even though the two objects are the same size.

The property of matter that indicates the amount of material packed into a given volume is called **density.**

1. In words:

Density depends both on the kind of atoms from which a material is made and on how closely they are packed together.

2. In an equation with words:

Density equals mass divided by volume.

3. In an equation with symbols:

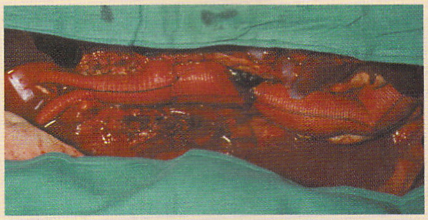
$$\rho = \frac{m}{V}$$

where the Greek letter ρ (rho) is customarily used to denote density.

Physics and Modern Technology—Materials Science

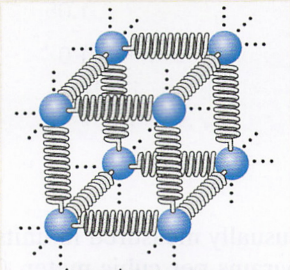
The products and devices of today could not have been imagined as recently as 50 years ago. In large part that's due to advances in understanding how atomic structure affects the properties of a material. This knowledge has led to the development of new materials for visual display, sports, medicine, housewares, and everything in between.

Light-emitting diodes (LEDs) emit light when an electric current runs through them. They provide visual displays for hand-held telephones.



Dacron was originally developed as a synthetic clothing material but is also used today for synthetic blood vessels.

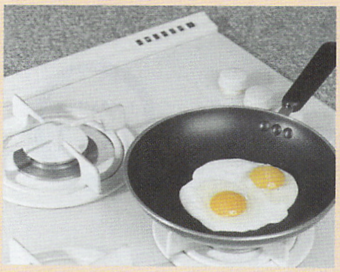
Titanium alloys provide lightweight metal parts of outstanding strength and durability for everything from airplanes to bicycles to golf clubs.



Atomic structure

Plastics made from petroleum by-products are used for everything from CD cases to styrofoam cups, keys to water bottles.

Liquid crystal displays (LCDs) allow light to pass through them when an electric current makes them align properly. You see them in calculators, watches, clock radios, and computer screens.



Teflon was discovered by accident but has become synonymous with nonstick cooking pans and utensils.

TABLE 10-1 Densities of Common Materials

Material	Density (grams/cubic centimeter)	Density (kilograms/cubic meter)
Solids		
Gold	19.3	19,300
Lead	11.3	11,300
Iron	7.9	7900
Diamond	3.5	3500
Aluminum	2.7	2700
Quartz sand	2.65	2650
Concrete	2.3	2300
Bone	1.8	1800
Ice	0.92	920
Wood (pine)	0.5	500
Liquids		
Mercury	13.6	13,600
Blood	1.05	1050
Water at 4°C	1.0	1000
Ethyl alcohol	0.79	790

Density is usually measured in units of grams per cubic centimeter or, in SI, in units of kilograms per cubic meter. (Note that a numerical value in kg/m^3 is exactly 1000 times larger than the value in g/cm^3.) A cubic centimeter of water at 4°C has a mass of 1 gram, so its density equals 1 g/cm^3. In this system of units, then, the density of any material tells you how much more, or less, massive a given volume of that material is compared to the same volume of water. The densities of some common substances are given in Table 10-1.

EXAMPLE 10-1

A Dense Metal

A cube of the platinum-like metal osmium measures 10 cm on a side and is found to have a mass of 22.6 kg. What is the density of osmium?

REASONING AND SOLUTION: Density is mass (in grams) divided by volume (in cubic centimeters). The mass is 22.6 kg, or 22,600 g, while the volume of the cube is given by

$$\begin{aligned} V &= \text{Length} \times \text{Width} \times \text{Height} \\ &= 10\text{ cm} \times 10\text{ cm} \times 10\text{ cm} = 1000\text{ cm}^3 \end{aligned}$$

Substituting these numbers:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

$$= \frac{22{,}600 \text{ g}}{1000 \text{ cm}^3}$$

$$= 22.6 \text{ g/cm}^3$$

In point of fact, osmium is the densest naturally occurring material at the Earth's surface. This metal is dense because it has massive atoms packed closely together. It is used in making hard, long-lasting metal alloys, including the metal used for some types of pen tips. ●

Develop Your Intuition: Density of Iron

What is the density of a 500-kilogram block of iron compared to an iron filing?

Density depends on a material's atomic structure, but does not depend on how much material there is. A 500-kilogram block of iron, in other words, has exactly the same density as an iron filing. The block's greater mass is accompanied by a greater volume, so when we divide mass by volume, we always get the same density.

PRESSURE

The properties of liquids and gases are different from those of solids in some important respects. In this section we examine some concepts associated with liquids and gases, which together are often referred to as *fluids.*

When you go to a gas station, you may use a gauge to check the air pressure in your tires, and you may use a pump to inflate them. In atomic terms, what are you doing when you carry out these everyday operations?

Air is a gas and, as we showed in Chapter 9, molecules in the gas constantly strike the walls of the tire. The tire exerts a force on the molecules that changes their direction, and hence, from Newton's third law of motion, the molecules exert a force on the tire. This force causes pressure, which is defined as follows.

When you measure the air pressure in a tire, you are actually measuring the difference between the pressure inside the tire and atmospheric pressure outside the tire.

1. In words:

Pressure *is a force divided by the area over which the force is exerted.*

2. In an equation with words:

Pressure equals force divided by area.

3. In symbols:

$$P = \frac{F}{A}$$

Actually, in the case of a car tire, two pressures are involved—an outward pressure exerted by the air in the tire and an inward pressure exerted by the atmosphere on the outside of the tire. By adding air to the tire, you increase the rate of collisions that contribute to the pressure inside the tire, so that the outward pressure exceeds the inward pressure and the tire expands. When you measure the pressure with a tire gauge, what you measure is the difference between these two pressures, a quantity called "gauge pressure." In a properly filled tire, the outward pressure from the air inside the tire is greater than the inward pressure from the air outside the tire; the material of the tire stretches to maintain that pressure difference.

The units of pressure in the English system are pounds per square inch (psi). This is the unit on an ordinary tire gauge. In SI, the unit of pressure is the pascal (Pa), which is defined to be a force of 1 newton exerted over an area of 1 square meter. The pascal is named in honor of Blaise Pascal (1623–1662), a French scientist and mathematician, who helped establish the study of statistics and did pioneering work in fluid mechanics.

Develop Your Intuition: Units of Pressure

Is a pressure of 1 Pa (a newton per square meter) bigger or smaller than a pressure of 1 psi (a pound per square inch)?

One meter is about 1 yard long and 1 yard is 36 inches. One square meter, therefore, contains approximately $(36)^2$, or over 1000, square inches. One newton, on the other hand, is the weight of approximately 0.1 kg, which is less than 1 pound. One pascal, then, represents a force smaller than 1 pound exerted over an area one thousand times larger than 1 square inch. Therefore, 1 pascal is much smaller than 1 psi. (In point of fact, everyday pressures are usually measured in a unit known as the megapascal, MPa, which is 1 million pascals.)

The Pressure–Depth Relationship

Water behind a dam, air in a balloon, mercury in a barometer, and lava in a volcano—in these and many other natural situations fluids exert pressure on their surroundings. Physicists have put considerable effort into understanding the relationship between a fluid's depth and the resulting pressure.

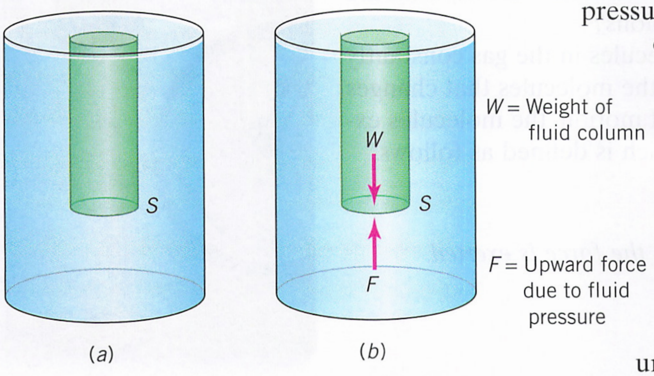


FIGURE 10-1. Pressure–depth relationship. (*a*) A column of the fluid above an area *S*. (*b*) The weight of the fluid column must be balanced by the upward force associated with the pressure on *S*.

Imagine the situation shown in Figure 10-1, in which a column of fluid is isolated from its surroundings by a flexible membrane (think of the membrane as an oddly shaped balloon). The fluid might be water in a lake or ocean, the air outside your window, or oil in a hydraulic lift used by your auto mechanic to lift your car. Consider the bottom surface of the membrane, labeled S in the figure. This surface doesn't move, so by Newton's first law of motion, the forces on it have to balance. These forces are (1) the downward weight of the column of fluid above S and (2) the upward force due to the pressure of the fluid outside the membrane. (The fluid inside the membrane exerts an equal and opposite pressure, but that pressure acts on a different object, namely the fluid on the outside of the membrane.) In order for the surface to remain stationary, these forces must balance. Let's summarize this relationship.

1. In words:

   The weight of the fluid column must be balanced by the force associated with the upward pressure on S.

2. In an equation form:

   The weight of the fluid column equals the fluid pressure times the area of *S*.

3. In an equation with symbols:

$$W = P \times A$$

   where A is the area of the surface, W is the weight of the column, and P is the fluid pressure at the bottom of the column.

If we concentrate for the moment on liquids such as water and oil, we can simplify this equation. Many liquids are approximately *incompressible*—that is, their density does not change much with pressure. In this case, the density of liquid in the column in Figure 10-1 is the same throughout the column, so that the weight of liquid in the column is

$$\begin{aligned} W &= \text{Density} \times \text{Volume} \times g \\ &= \rho \times (A \times d) \times g \end{aligned}$$

where d is the height of the column or, equivalently, the depth below the fluid surface of the bottom membrane S, and g is the acceleration due to gravity. (Remember that weight is equal to mass times g.) If we insert this expression for weight into the equation $W = P \times A$, the quantities A cancel on both sides of the equation, and we find

$$\begin{aligned} P \times A &= \rho \times (A \times d) \times g \\ P &= \rho \times d \times g \end{aligned}$$

In other words, in a liquid, the pressure increases with depth—double the depth and you double the pressure.

Two points should be made about the pressure exerted by a fluid. First, although we have concentrated on the upward force due to pressure, in fact the pressure at any point in a fluid is the same in all directions because pressure is related to collisions of atoms or molecules, which also move in all directions.

The second point is that it makes no difference how much fluid is involved in our considerations. The water pressure 3 feet beneath the surface of a backyard swimming pool is exactly the same as the pressure 3 feet beneath the surface of the Atlantic Ocean (aside from a small difference due to the different densities of these two bodies of water.) For a given liquid, pressure depends on depth and nothing else (Figure 10-2). (This statement is true for a static fluid; that is, one with no motion. We look at moving fluids later in this chapter.)

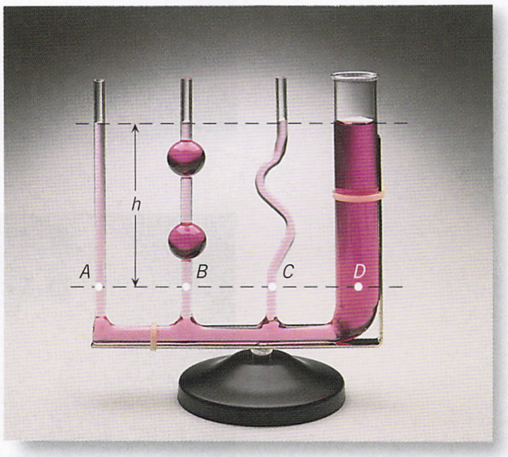


FIGURE 10-2. The levels of water in a series of connected glass tubes are the same, independent of the shapes of the tubes.

Connection

The Design of Dams

A dam is a structure designed to hold back water flowing in a river. Typically, the water behind a dam forms a lake, and the sideways pressure exerted on the dam by the water piled up behind it increases with depth. The deeper the lake, the greater the pressure at the bottom of the dam, regardless of how much water is in the lake. This is why dams are usually much thicker at the bottom than at the top.

The earliest dams, built centuries ago, were made of packed earth and were intended to collect river water into a lake so the water could be used to irrigate fields. Over the years, the design and construction of dams evolved as engineers applied new ideas and new technology to these massive projects. Dams built across canyons were designed in a circular arch, curving away from the water; this design channeled the force of the water along the face of the dam to its ends, so the rocky sides of the canyon could help support the dam (Figure 10-3). The largest dams are built of concrete, a material that supports large pressures without cracking, The Hoover Dam at the Nevada–Arizona border is built in an arch and contains about 6.6 million tons of concrete; it was designed as a hydroelectric dam and supplies electricity to Las Vegas, among other areas.

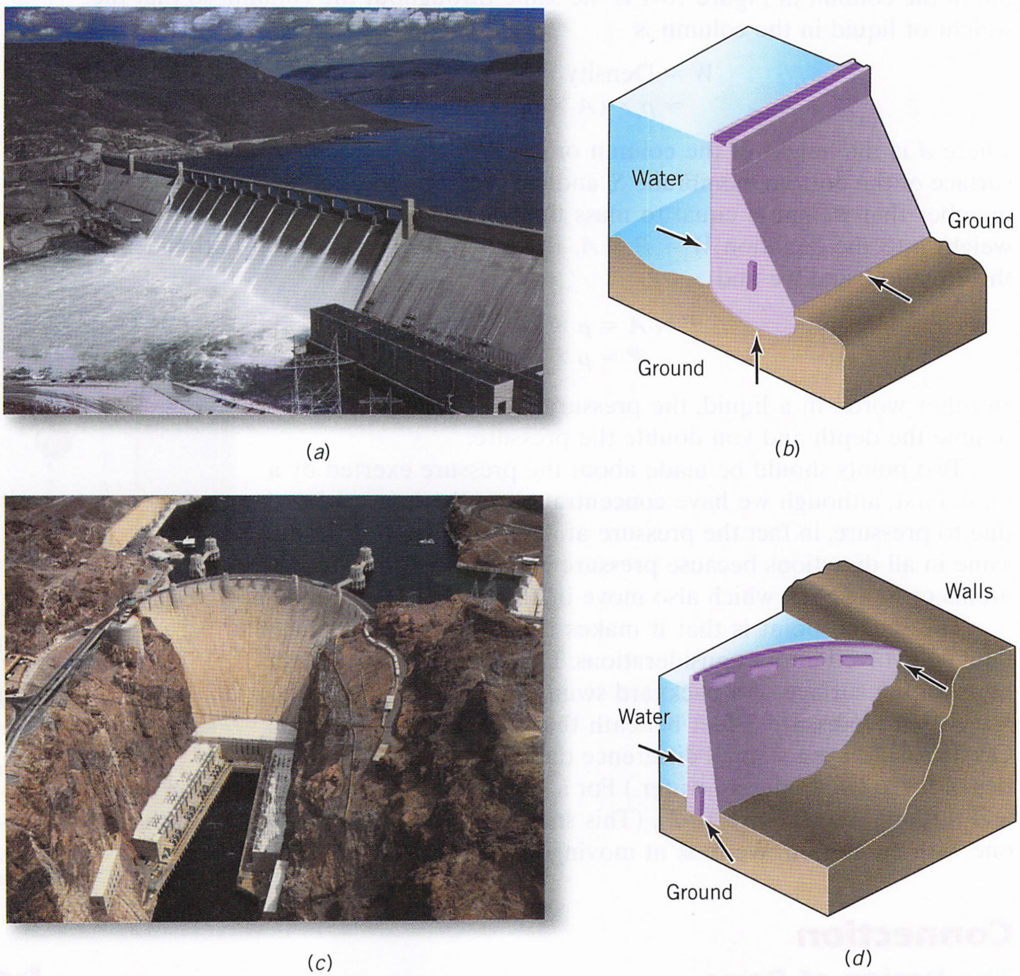


FIGURE 10-3. A big dam must withstand a great deal of pressure from the water against it. Gravity dams (*a*, *b*) and arch dams (*c*, *d*) are designed to transfer some of the forces due to that pressure to the ground and canyon walls where the dam is built.

The same principles apply to the design of large aquariums, whose windows need to be transparent while still holding back huge amounts of water. For example, the Monterey Bay Aquarium contains one of the largest windows in the world—54 feet long and 15 feet high—to offer visitors a view of the ocean.

Large tanks are often used to hold liquids in storage; these tanks must be strong enough to withstand the forces that develop from the pressure of the liquid. A disastrous example was the 1919 rupture of a metal tank used to store molasses in Boston. The tank was 90 feet high and 90 feet across, which meant it had to withstand forces at the bottom of over 2.5 million pounds. The flood of molasses released was initially 30 feet high, trapping and killing pedestrians and horses in its sticky ooze. The cleanup lasted for several weeks.

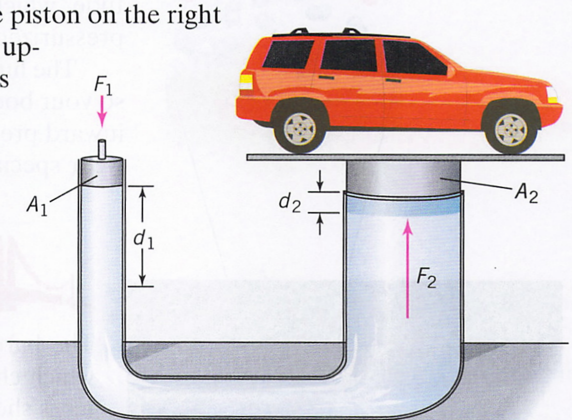
Connection

The Hydraulic Lift and Pascal's Principle

Our understanding of the physical behavior of fluids under pressure has led to numerous everyday practical applications. We now know that pressure is a property of atomic or molecular collisions. Therefore, if you increase the pressure of a static fluid in one place (by pushing on a plunger, for example), the collisions transmit that increase immediately to every part of the fluid. This immediate transmission of pressure to all parts of a fluid, known as **Pascal's principle,** explains the working of the hydraulic lift (Figure 10-4) that allows a mechanic to lift your car by exerting a small force.

The basic idea is that pushing down on the plunger shown on the left of Figure 10-4, increases the pressure throughout the fluid. If the piston on the right has a larger area than the plunger on the left, then the total upward force on that piston, which is equal to the pressure times the area of the plunger, is greater than the downward force exerted on the plunger on the left. This arrangement doesn't violate the law of conservation of energy because you have to move the plunger on the left through a greater distance. The work done—the product of force times distance—is the same for both plunger and piston.

Pascal's principle is the basis for all hydraulic systems and is involved wherever it is useful to produce a large force by exerting a small one. For example, the control



$$\text{Pressure}_1 = \text{Pressure}_2$$

$$\frac{F_1}{A_1} = \frac{F_2}{A_2}$$

$$F_2 = F_1 \times \frac{A_2}{A_1}$$

$$\text{Work}_1 = \text{Work}_2$$

$$F_1 d_1 = F_2 d_2$$

$$d_2 = d_1 \times \frac{F_1}{F_2}$$

FIGURE 10-4. Mechanical lift in an auto repair shop. A small force moving a large distance is transformed into a larger force moving a smaller distance.

Hydraulic mechanisms provide strong forces for controlling wing flaps on an airplane or plows on a bulldozer.

systems that operate the wing flaps and rudders on airplanes are usually hydraulic. Contemporary automobiles often use hydraulic systems to aid the driver in controlling both the brakes and the steering wheel. And in industry, large hydraulic presses are often used to shape metals into objects such as coins, office furniture, and machine parts. ●

Atmospheric Pressure

Like the liquid shown in Figure 10-1, gas in a large body such as Earth's atmosphere exerts a pressure that depends on the depth of the gas. Unlike liquid water or oil, however, the density of gas in a column above a point on the Earth's surface is not constant. Gas density is greater at the bottom of a column than it is higher up (Figure 10-5). As anyone who has hiked in the mountains can attest, the density of air at an elevation of 10,000 feet is considerably less than at sea level. By the time you get to about 100,000 feet, you are above 99 percent of the atmosphere.

Nevertheless, the air in the column above the Earth's surface weighs something, and that weight must be balanced by a pressure, just as in a liquid. If you hold out your hand at sea level and imagine drawing a square 1 inch on a side, then the column of air that extends from your hand into space will weigh precisely 14.7 pounds (or about 65 N). Thus, the atmospheric pressure at sea level is 14.7 psi. Atmospheric pressure drops off rapidly with altitude, which explains why airline passenger compartments have to be pressurized.

The human race evolved at the bottom of Earth's atmospheric ocean, so your body automatically exerts an outward pressure to counteract the inward pressure exerted by the atmosphere. This is why astronauts must wear special suits when they work in the vacuum of space.

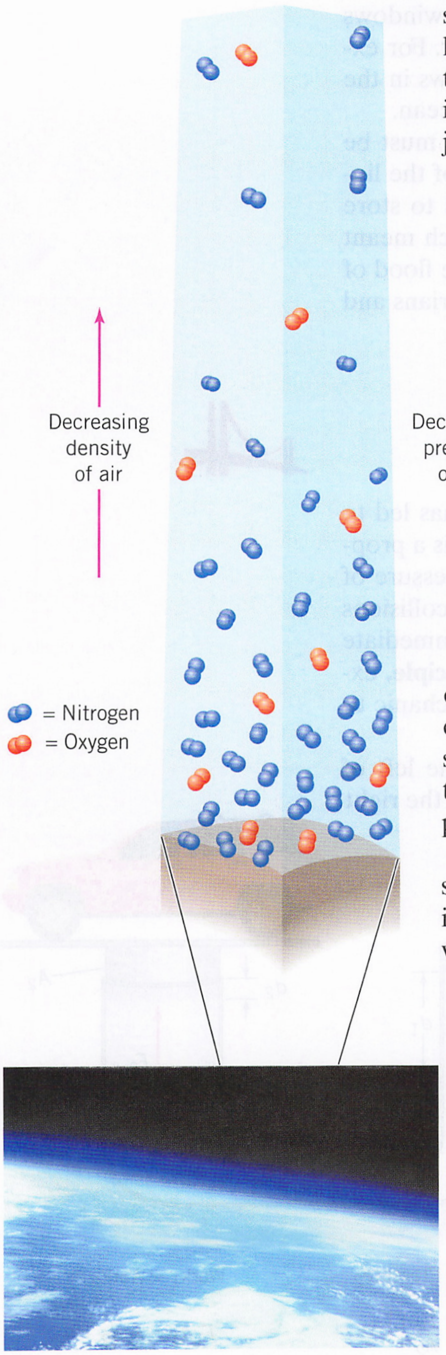


FIGURE 10-5. Gas density in Earth's atmosphere. The pressure of the atmosphere at sea level is about 101,000 pascals (14.7 psi) and fades away to practically nothing at an altitude of 50 kilometers.

Connection
The Barometer

The barometer is an instrument for measuring atmospheric pressure, which changes due to several different factors. A very simple barometer is shown in Figure 10-6. A long tube, open at one end and closed at the other, is filled with a dense liquid, such as mercury. The tube is then inverted into a bowl of the same dense liquid, with the closed end sticking up. The column of liquid in the tube starts to fall, but is opposed by the pressure of the atmosphere, pushing down on the surface of the liquid in the bowl. The level of liquid in the column can be calibrated to indicate normal atmospheric pressure. When atmospheric pressure drops, the weight of liquid that can be supported in the column drops, and the height of the liquid column falls. The reverse happens when atmospheric pressure rises.

Readings of atmospheric pressure—called "barometric pressure"—are one of the basic kinds of data for meteorology, the science of weather. In general, low barometric readings correspond to bad weather—clouds, rain, or snow—and high readings correspond to blue skies and fair weather. You've probably seen weather forecasts on television showing the progress of low-pressure systems and high-pressure systems as they follow the wind patterns of the atmosphere. The differences between high- and low-pressure systems are not large on a barometer, amounting to a few inches of height in the barometer's mercury column. (Normal barometric pressure is considered to be 30.00 inches of mercury. The lowest reading ever recorded in the northeastern United States, during the great 1938 hurricane, was 27.94 inches.) But these differences reflect changes in vast volumes of air in constant motion around Earth. Understanding these pressure readings and fitting them into the picture of temperature readings, measurements of wind speed and direction, and relative humidity form the basis for weather forecasting. ●

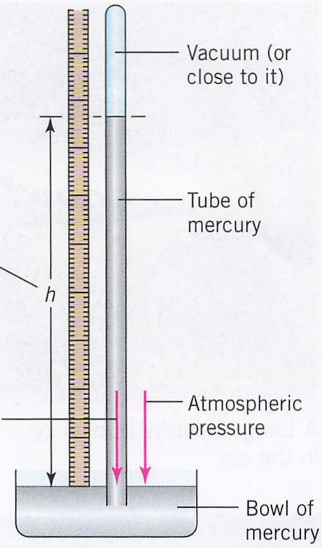


FIGURE 10-6. A barometer measures atmospheric pressure at a given time and place.

Buoyancy and Archimedes' Principle

Another intriguing property of fluids occurs because solids displace fluids. For example, when you get into a bathtub, the level of water in the tub rises. Every time you take a bath, you demonstrate what is now known as *Archimedes' principle,* named after the Greek scientist and mathematician Archimedes of Syracuse (287–212 B.C.). His principle deals with the force exerted by a fluid on an immersed object.

Think about a volume of material under the surface of a fluid, as shown in Figure 10-7. A volume of the fluid itself will not move but will be in equilibrium. Fluid pressure will exert force all around, greater at the bottom than at the top to support the weight of this volume of fluid. Now, if the molecules of a material, such as a rock or a piece of wood, are different from those of the fluid, the pressure around the object will still be the same, because the molecules of the fluid haven't changed. They will still exert the same forces on the object, including a net upward force. What has changed is the weight of the object. If the object's weight is greater than the upward force exerted by the fluid, the object sinks. If the object's weight is less than the upward force of the fluid, the object floats. This is the molecular basis of Archimedes' principle, which states that

The upward force exerted on an object immersed in a fluid is equal to the weight of the fluid that the object displaces.

The force exerted by the fluid on the object is called the **buoyant force** and the effect is known as buoyancy. Buoyancy explains why it is easier to lift something—a child, for example—under water than in the air. The force needed to lift the child is her weight minus the upward buoyant force—the weight of the

Fluid presses against arbitrary volume of fluid; force is greater at bottom of volume due to greater pressure

Fluid presses against object of same shape; pressure is still greater at bottom, providing net upward force

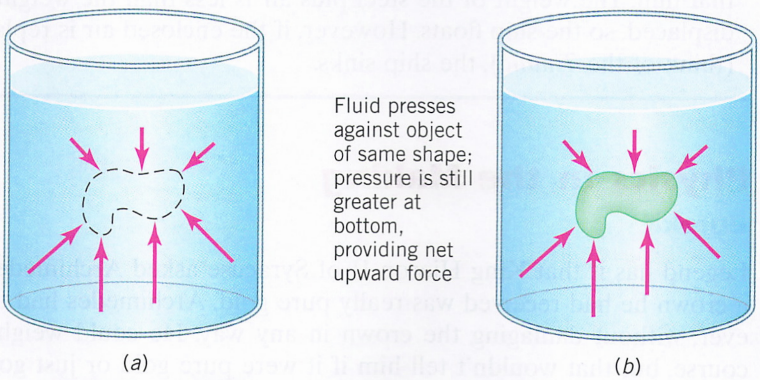
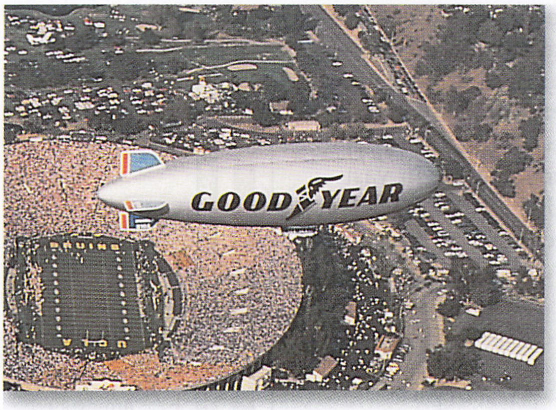


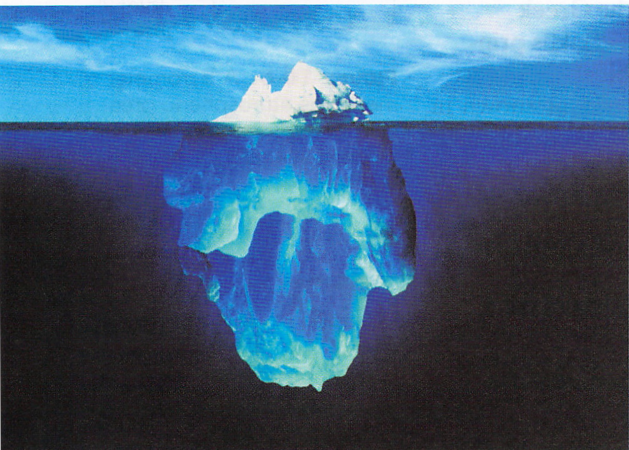
FIGURE 10-7. (*a*) A fluid exerts pressure on all sides of any arbitrary volume of the fluid; the pressure is greater at a greater depth. (*b*) For an object of the same shape immersed in the fluid, a net upward force (buoyant force) acts on the object.



A blimp exhibits buoyancy in the air.

displaced water. For this reason, people undergoing physical therapy after a serious injury often spend time exercising their muscles while in water, where the force needed to support the body is less.

Archimedes' principle also explains why some objects float in water while others sink. If the weight of the object is greater than that of the displaced water, the net force on the object is downward and it sinks. On the other hand, if the weight of the object is less than the weight of the fluid it displaces, the upward buoyant force pushes the object to the surface. In fact, the buoyant force keeps pushing upward until the amount of material below the water line displaces just enough water to equal the object's weight. This fact means that objects with a density greater than that of water sink, whereas objects with a lower density than water float.



An iceberg floats with 10% of its mass above the surface of the water because ice is only 90% as dense as water.

Archimedes' principle applies to all fluids, not just water. The buoyant force explains why blimps and hot-air balloons can travel through the air. Blimps are filled with lighter-than-air gases such as helium so that their average density (including the steel gondola containing passengers, crew, and engines) is less than that of the air. In a hot-air balloon, air is heated so it will expand and have a lower density than the surrounding air outside the balloon.

Archimedes' principle explains what people mean when they say, "That's only the tip of the iceberg." Ice has a density about 90% that of water. Thus, 90% of an iceberg's volume has to be hidden under the water's surface to produce a buoyant force equal to the iceberg's weight. What you see above water (the tip) is only 10% of what's actually there.

Develop Your Intuition: Can Steel Float?

We know that a piece of steel will sink if it's placed in water, so how can ships made of steel stay afloat?

The total amount of water displaced by a boat is the volume of the steel hull (or that part of the hull under water) *plus* the volume of air enclosed in that hull. The weight of the steel plus air is less than the weight of the water displaced, so the ship floats. However, if the enclosed air is replaced by water (think of the *Titanic*), the ship sinks.

Physics in the Making

Eureka

Legend has it that King Hieron II of Syracuse asked Archimedes to find out if a crown he had received was really pure gold. Archimedes had to do this, however, without damaging the crown in any way. He could weigh the crown, of course, but that wouldn't tell him if it were pure gold or just gold plate over a metal such as lead. Then, while getting into his bath one day, he saw the water in the tub rise and received an inspiration. He realized that if he put the crown under water, he could find its volume by seeing how much water it displaced. In modern language, he realized that he could measure both the mass and the volume of the crown and thus determine if its density matched that of gold.

Archimedes was so excited that he jumped out of his bath and raced through the streets to the palace, shouting, "Eureka!" ("I have found it!"). Different versions of the legend disagree as to whether he stopped to put his clothes on first. ●

Fluids in Motion: The Bernoulli Effect

One of the most remarkable and useful aspects of fluid properties is that fluids in motion exert pressures differently than fluids at rest. Daniel Bernoulli (1700–1782), a member of a family of contentious Swiss philosophers, mathematicians, and scientists, investigated the pressure exerted by fluids in motion. He found that he could summarize his results in a simple form:

The pressure exerted by a fluid on a surface decreases as the velocity of the fluid across the surface increases.

We won't derive the equation that describes this **Bernoulli effect,** but it is simply an expression of conservation of energy for a moving fluid.

Bernoulli's principle explains in part how an airplane can stay aloft, even though it is heavier than the air it displaces. Next time you are at an airport, look at the wings of the planes you see there. You will notice that they are designed like the one shown in Figure 10-8, so that the upper part of the wing is more curved than the lower part. This shape is known as an "airfoil." When the plane starts to move down the runway, the air through which it moves has to travel faster over the top surface of the wing to catch up with the air moving under the bottom surface. By Bernoulli's principle, this means that the pressure on the top of the wing is less than it is on the bottom, so there is a net upward force, called **lift.** When the plane is moving fast enough, the lift force exceeds the weight of the plane and the plane lifts off the ground. Next time you fly, watch the wing during takeoff. On some aircraft, the wing is flexible enough so that you can actually see the tip moving upward just before the plane leaves the ground. (The

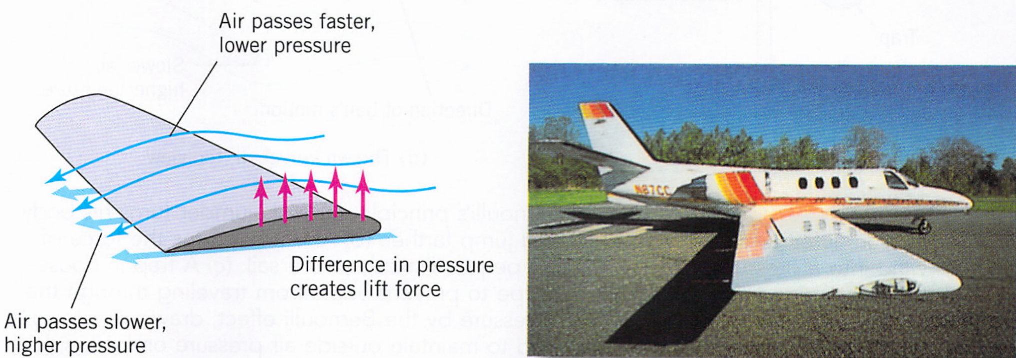


FIGURE 10-8. Bernoulli's principle. The pressure exerted by a fluid on a surface decreases as the velocity of the fluid across the surface increases.

Bernoulli effect is not the only principle involved in producing lift on an airplane. At least as important is Newton's third law. The shape of the wing also directs air downward as it passes the wing, giving the air a downward change in momentum. The reaction to this momentum change is an upward force acting on the plane.)

The airfoil shape appears in many different guises (Figure 10-9). For example, ski jumpers stretch far out over their skis to give their bodies an airfoil shape, helping produce a lift that takes them farther down the slope. The filled sails on a sailboat have the shape of a vertical airfoil, producing a horizontal force instead of a lifting force. Even many species of fish have evolved into airfoil-like shapes to produce more of a lifting effect as they swim through the water.

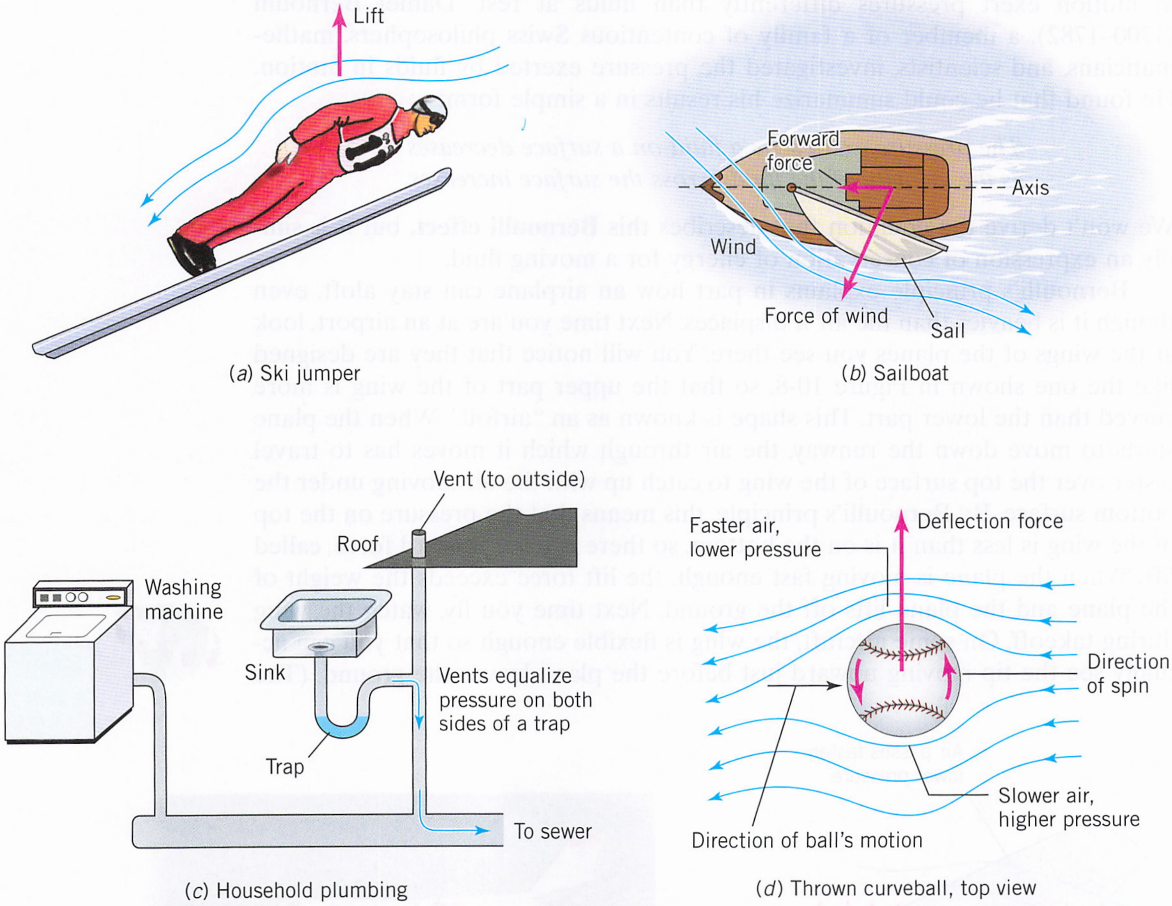


FIGURE 10-9. Other examples of Bernoulli's principle. (*a*) A ski jumper turns his body into an airfoil to obtain vertical lift and jump farther. (*b*) A sailboat turns the force of wind into a pressure difference acting perpendicularly to the sail. (*c*) A trap in household plumbing maintains water in a pipe to prevent odors from traveling through the system. Flushing water could lower pressure by the Bernoulli effect, drawing water out of the trap, so vents must be provided to maintain outside air pressure on both sides of the trap, even with fast-running water in the connecting pipes. (*d*) The seams of a baseball move a layer of air around the ball as it spins, but the leading edge of the ball moves through the air faster, causing a sideways deflection.

THE IDEAL GAS LAW

The topics we have discussed in the last few sections—the pressure-depth relationship, Pascal's principle, Archimedes' principle, and the Bernoulli effect—apply to all fluids, whether liquid or gas. However, gases exhibit some unique behaviors that do not occur in liquids or solids.

During the eighteenth century, scientists made many experimental studies of the properties of gases. Two important results are:

1. If the pressure on a gas is held constant, the volume increases proportionally to the temperature (Charles's law).
2. If the temperature of a gas is held constant, the volume decreases proportionally with increases in pressure (Boyle's law).

Both of these laws (as well as others like them) conform with our everyday experience. If you squeeze a gas, its volume decreases (Boyle's law); if you heat a gas, it expands (Charles's law). Today, we summarize these kinds of results in a single equation, called the **ideal gas law.** As the name implies, this law does not apply exactly to any real gas, but it's a very good approximation for describing the behavior of all gases.

1. In words:

   For a fixed amount of gas, the pressure, volume, and temperature of any gas are related to one another in a way consistent with Charles's and Boyle's laws.

2. In an equation with words:

   For a fixed amount of an ideal gas, the product of pressure and volume divided by the temperature is a constant.

3. In an equation with symbols:

$$\frac{PV}{T} = \text{Constant} \qquad \text{or} \qquad \frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

   where P, V, and T are the pressure, volume, and temperature of the gas; the subscripts refer to these properties for two different conditions of the gas.

Notice the following features of the ideal gas equation:

1. If the temperature is held constant, then the product of pressure and volume does not change. Consequently, if the pressure increases, then the volume must decrease, and vice versa. This is Boyle's law.
2. If the pressure is held constant, then the equation says that the volume is proportional to the temperature. This is Charles's law.
3. When we're using the ideal gas law, temperature must be measured on the Kelvin scale. We describe the Kelvin scale in more detail in Chapter 11; for now, you just need to know that temperatures on this scale are measured in kelvins. Kelvins are equal in *size* to degrees on the common Celsius scale, but the Kelvin scale begins at absolute zero (the lowest temperature possible), which is $-273°$ on the Celsius scale. The freezing point of water is 0°C or 273 kelvins, while the boiling point of water is 100°C or 373 kelvins.

Develop Your Intuition: Checking Tire Pressure

It is important to keep the tires on your car properly inflated. Why shouldn't you measure that inflation immediately after a long drive?

The reason is that friction with the road heats the tire. Since V is approximately constant, the increase in T creates a corresponding increase in P. This effect means that the pressure you read from a hot tire will be higher than it would be if the tire were cold.

ELASTICITY

All around us, every moment of our lives, materials respond to stress. The floor of your room bends slightly as it supports your weight. Plastic grocery bags stretch as you cram them full of food. The arteries in your body swell from your blood pressure. These responses and many more are examples of *elasticity,* which is a term used to describe the way that materials change shape under the influence of external forces. Physicists have studied this fundamental material property for more than 3 centuries.

Hooke's Law

A thin wire provides a simple, one-dimensional example of elasticity. If an external force is applied to a wire—for example, by hanging a weight from it—the configuration of the wire's atoms changes in response. The "springs" between the atoms stretch and the wire gets longer. This stretching of the material is described by *Hooke's law,* named after the English scientist Robert Hooke (1635–1702).

1. In words:

The harder you pull on something, the more it stretches.

2. In an equation with words:

The change in length of a material is proportional to the applied force.

3. In an equation with symbols:

$$F = k\Delta L$$

where ΔL is the change in length and k is a constant that varies from one material to the next. Once the force is removed, the wire returns to its original length.

A rubber band provides a familiar example of Hooke's law. Pull on a rubber band and it stretches, pull harder and it stretches more, as the law says—but only to a point. If you stretch a rubber band (or anything else) too far, it loses its elasticity and won't stretch any farther. In fact, it may even break. Once this *elastic limit* is reached, Hooke's law no longer applies. The internal arrangements of atoms and chemical bonds have been permanently changed. Bonds have been broken and the material is not the same as it was when the stretching began.

Tension and Compression

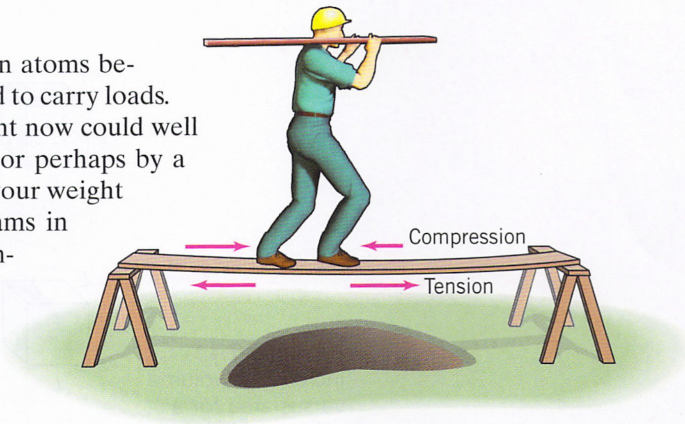


FIGURE 10-10. A plank supported at each end (not clamped) bends downward a little bit as you walk across it. The top of the plank is slightly compressed, while the bottom of the plank is under tension.

Another situation in which internal bonds between atoms become important occurs when materials are required to carry loads. For example, the floor on which you are sitting right now could well be held up by a series of wooden or steel beams or perhaps by a concrete slab. Every time you drive over a bridge, your weight (and the weight of your car) is supported by beams in the bridge. From the tallest skyscraper to the humblest cottage, ceilings and floors carry weight and support loads, and it is the interatomic "springs" that actually make these systems work.

Take, for example, a plank supported at both ends, as shown in Figure 10-10. You might come across a plank like this being used as an impromptu bridge on a wilderness trail or a construction site. When you stand on the plank, it bows down in the middle, as shown. In this situation, the atoms along the top of the plank are pushed together, compressing the interatomic bonds along the top of the beam. We say that the top of the beam is under **compression.** At the same time, the atoms along the bottom of the beam are pulled apart, causing the interatomic bonds there to stretch. The bottom of the plank is said to be under **tension.** It is the combination of these forces—the springs along the top pushing and the springs along the bottom pulling—that produces the force that supports your weight.

Over time, engineers have found that some materials, such as steel, support tension better than other materials; this is why steel is used for suspension cables in bridges and for other situations where tension is the main concern. Materials such as concrete support compression better than tension and are used for the foundations of tall buildings, for dams, and for other compressive functions. Ultimately, the differences in behavior of these materials can be traced back to the arrangements of their atoms and molecules.

Develop Your Intuition: Prestressed Beams

Concrete beams for highway bridges are often built so that they bow upward in the middle before they are installed. This is called "prestressed" concrete. Why is the beam made this way?

In this case, when the weight of a load is applied to the beam and it deforms downward, it will actually be straight. This minimizes the stress on the beams when they carry the load.

Scaling

In Chapter 3 we talk about Galileo Galilei's contributions to experimental physics. Galileo was an important figure in Italy, where he served as a consultant to many important government offices. In particular, he was a consultant at the Arsenal of Venice, the greatest naval shipyard of its time. People there were trying to build bigger ships, and they encountered a vexing problem: if they scaled up the design of a successful smaller ship, there were all sorts of problems with the result. Why wouldn't simple scaling work?

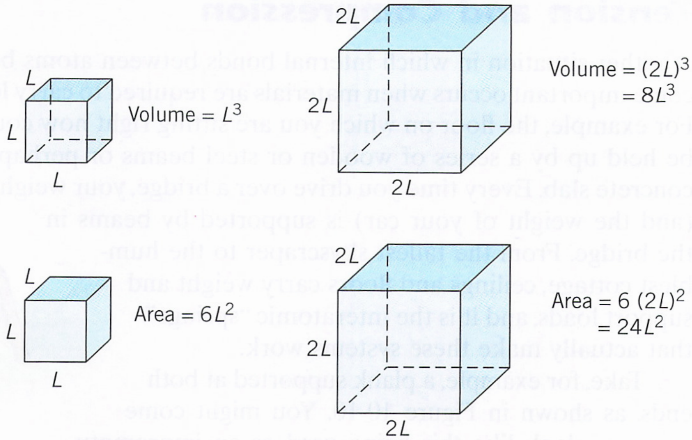


FIGURE 10-11. Increase in volume versus area for a cube.

This question took Galileo into a study of the properties of materials and gave him an important insight into the relation between large and small structures. You can get a sense of his work by thinking about a simple problem. Imagine that you have a cube of material as shown in Figure 10-11 and you want to double its size. If the original cube is of length L on each side, then the doubled cube is of length $2L$.

This doubled cube is not as strong (for its size) as the original. Why not? Because the volume (and therefore the weight) of the doubled cube is eight times the weight of the original, but the surface area that must support that weight is only four times as big as the original. In other words, when we scale things up, the weight to be supported grows faster than the area available to support it.

Many consequences follow from this simple fact. One, relevant to the Physics Around Us section at the beginning of this chapter, is that an elephant is not only bigger than an ant, but it also looks different. The elephant's legs are much thicker in proportion to its body, for example. This difference arises because as the weight of an animal doubles, so must the cross-sectional area that carries the weight (in this case, the elephant's legs). The exact same principle applies to the size of columns that support tall buildings and the size of tires that support giant trucks.

THINKING MORE ABOUT

Modern Materials

Almost every material on Earth is easily classified as a solid, a liquid, or a gas, based on the arrangement and bonding of its atoms or molecules. But in the late nineteenth century, scientists synthesized an odd intermediate state of matter, called "liquid crystals." These materials are now used in many kinds of electronic devices, including the digital display of your pocket calculator.

The distinction between a liquid and a crystal is one of atomic-scale order: positions of atoms are disordered in a liquid, but ordered in a crystal. But think about what happens in the case of a liquid formed from very long and slender molecules. Like a box of uncooked spaghetti, in which the individual pieces are mobile but well oriented, these mol-

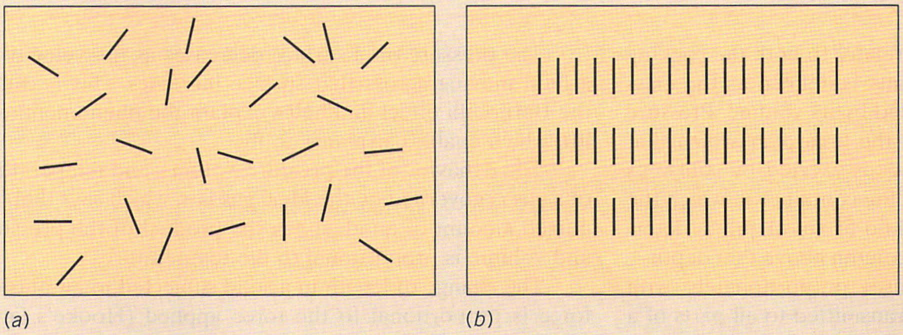


FIGURE 10-12. Schematic diagram of a liquid crystal. Under normal circumstances the elongated molecules are randomly oriented (*a*), but under special circumstances the molecules align in an orderly pattern (*b*).

ecules may adopt a very ordered arrangement even in the liquid form.

Under special circumstances (for example, when electricity passes near the liquid) all the molecules may align (Figure 10-12). This change in the arrangement of molecules causes a corresponding change in the physical properties of the liquid—a change that is used in a liquid crystal display.

Liquid crystals are also found in nature. Every cell membrane is composed of a double layer of elongated molecules called lipids (Figure 10-13). They separate the material inside the cell from its surroundings just as effectively as if they were solid. Many scientists now think that these "lipid bilayers" originated in the primitive ocean as molecules similar to today's liquid crystals.

As with many other novel materials, liquid crystals were an unexpected laboratory discovery that eventually found important practical applications. Given such chance findings, what should be the relative importance of funding basic versus applied materials research? Should the federal government fund materials research or should corporate laboratories take the lead in these efforts?

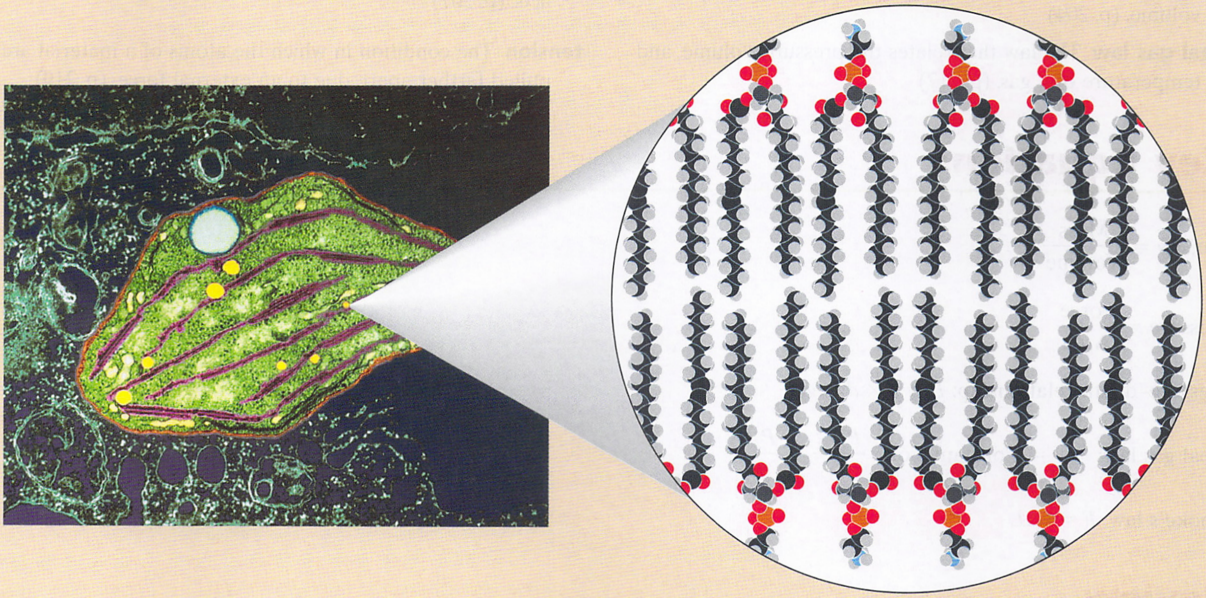


FIGURE 10-13. Cell membranes are composed of countless elongated lipid molecules that align into a bilayer, effectively separating the inside of a cell from the outside.

Summary

The **density** of a material, which relates to both the packing and the mass of a material's atoms, is defined as the mass of a sample of the material divided by its volume. **Pressure** is defined as a force divided by the area over which that force is exerted. Pressure in fluids is exerted by collisions between atoms or molecules and the container in which the fluid is held. The pressure in a fluid at any depth is determined by the weight of the fluid column above that depth—in a liquid, the pressure increases proportionately with depth. Changes in pressure are transmitted to all parts of a fluid, a rule known as **Pascal's principle.** Atmospheric pressure at sea level is approximately 14.7 psi or 0.1 MPa.

The upward force exerted on a body immersed in a fluid is equal to the weight of the fluid displaced (Archimedes' principle). This upward force is called the **buoyant force.**

The pressure on a surface decreases as the velocity of a fluid moving across that surface increases. This is called the Bernouilli effect and helps explain the phenomenon of **lift,** which enables airplanes to fly.

The behavior of the pressure, volume, and temperature of a gas is governed by the **ideal gas law,** which says that for a fixed amount of an ideal gas, the product of the pressure and volume is proportional to the temperature.

The change of length in a solid subjected to an outside force is proportional to the force applied (Hooke's law). Horizontal beams that support a load experience **compression** along their upper surfaces and **tension** along their lower surfaces. If an object is scaled up in size, the weight to be supported grows as the cube of the linear dimension, while the load-bearing surface grows only as the square.

Key Terms

Bernoulli effect The effect by which the pressure exerted by a fluid decreases as the fluid velocity increases. (p. 215)

buoyant force The upward force on an object due to the pressure of a fluid. (p. 213)

compression The condition in which the atoms of a material are squeezed closer together, due to an external force. (p. 219)

density The mass per unit volume of a substance; it is a measure of how much material is packed into a given volume. (p. 204)

ideal gas law The law that relates the pressure, volume, and temperature of a gas. (p. 217)

lift The net upward force on a wing due to the pressure difference between the top and the bottom of the wing. (p. 215)

Pascal's principle The statement that an increase of pressure of a static fluid in one place is transmitted immediately to every part of the fluid. (p. 211)

pressure A force divided by the area over which the force acts. (p. 207)

tension The condition in which the atoms of a material are pulled farther apart, due to an external force. (p. 219)

Key Equations

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

Pressure–depth relationship: $P = \rho \times d \times g$

Ideal gas law: $\frac{PV}{T} = \text{Constant}$ or $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$

Hooke's law: $F = k\Delta L$

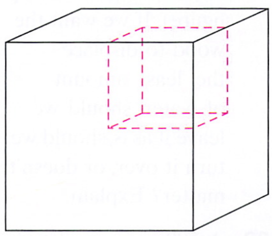
Review

1. What is density? What are its units?
2. What two basic reasons account for the given density of a material?
3. Which is denser, a 2-foot square cube of balsa wood, or a 1-inch cube of the same wood? Explain.
4. What is pressure? What are its units?

5. How is the pressure at the bottom of a column of water related to its depth?
6. Why are dams much thicker at the bottom than at the top?
7. What is Pascal's principle? How is an increase in pressure in one part of a system transmitted to another part of a system?
8. How does the atmospheric pressure at sea level differ from the pressure at the top of a high mountain?
9. What does a barometer measure? How does it work?
10. What is Archimedes' principle?
11. How does a hydraulic lift work? Explain in terms of Pascal's principle.
12. What are some practical devices that utilize Pascal's principle, other than the hydraulic lifts mentioned in the text?
13. What is buoyancy? Explain in detail how an object's density determines whether or not it will float.
14. Use your own words to explain just how Archimedes was able to determine whether the king's crown was really gold.
15. What is Bernoulli's principle? How does this account for the lift that keeps an airplane aloft?
16. What is Boyle's law? What is Charles's law?
17. What is the ideal gas law?
18. Describe Hooke's law. What is the equation for it and what implications does it have for an object's breaking point?
19. What is meant by the elastic limit of an object? What happens to a material when stretched beyond this limit?
20. What is compression at the atomic level? What is tension? What forces are involved in each case?
21. Why can't you make something larger and stronger simply by scaling it up in size using the same proportions? Could an ant be made the size of an elephant while keeping its same proportions?

Questions

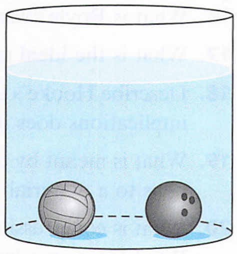
1. Is knowing only the density of a material enough to identify uniquely a material of unknown origin? Why or why not?
2. In everyday use, the word "dense" is often used interchangeably with the word "hard." In physics, density and hardness have completely different meanings. Which is denser, lead or diamond? Which do you think is harder?
3. Consider a cube of soft, spongy material. Which would result in a material with greater density: cutting out a piece of the cube that has one-eighth the volume (see figure), or compressing the cube until it has one-eighth the volume? Explain.



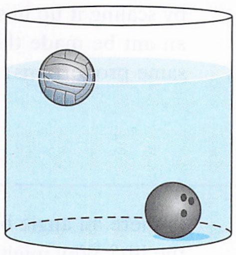
4. Consider two identical metal bottles that can be used to hold compressed gases. One is filled with air at atmospheric pressure, and the other is completely evacuated. Which bottle is heavier? Which bottle is denser? Explain.
5. Why are you weighed while submerged under water to determine your percentage of body fat?
6. Why do ice cubes float? Can you think of any possible ramifications for life in the oceans if this were not the case?
7. If you mixed oil and vinegar in one container, which would you expect to end up on top, and why?
8. Why does a plane extend flaps from its wings during take off and landing?
9. What happens when the angle of attack (the angle that a wing makes with the ground) increases as a plane climbs? Is there an angle beyond which it becomes detrimental to the lift? Why might this happen?
10. Would the pressure at the bottom of a 3-foot holding tank be different if the tank held motor oil instead of water? Why or why not?
11. If you triple the depth of a column of fluid, what happens to the pressure at the bottom?
12. How does the pressure in a 3-foot-deep lake differ from the pressure in a 3-foot-deep hot tub 2 meters in diameter? Explain.
13. Why do some iron objects, such as iron ships, float when placed in water while other iron objects, such as nails, sink?
14. If the pressure on a gas in a flexible closed container is increased and the temperature remains constant, what happens to the volume of the gas? What has to be done to the gas while it is being compressed in order to maintain constant temperature?
15. Under constant pressure and with a constant amount of gas present, what happens to the volume of the gas if the temperature increases? Similarly, under the same conditions, what happens to the temperature if the volume of the gas is suddenly increased?
16. Which is likely to hurt more, having your bare foot stepped on by a 270-lb man wearing flat-soled loafers or having your foot stepped on by a 130-lb woman wearing high heels? Explain.
17. If you submerge a flexible air-filled balloon under water, what happens to the balloon's density? Why?
18. A flexible helium-filled party balloon is released in the atmosphere. As it gains altitude, what happens to the volume of the balloon? What about its density?

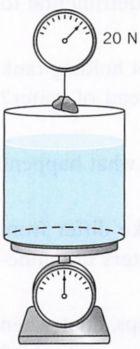
19. A helium-filled party balloon is released in the atmosphere. Imagine that the balloon is rigid, so that its volume cannot change. What happens to the buoyant force on the balloon as it gains altitude?

20. Suppose that a volleyball and a bowling ball are both completely submerged in water and have the same volume, as in the figure. (Of course, you would have to hold the volleyball beneath the water to keep it from popping up to the surface.) Which, if either, feels a greater buoyant force?



21. In the problem above, the volleyball is released and it floats up to the surface. The bowling ball, being denser than water, remains at the bottom (see figure). Which, if either, feels a greater buoyant force?





22. A 20-N rock hangs from a spring scale. The rock is lowered into a beaker of water that sits on another spring scale, but is not allowed to touch the bottom of the beaker (see figure). How do the readings on the two scales change?

23. Why do people who are rehabilitating from bone, muscle, and joint injuries often start their rehabilitation in pools? What role does buoyancy play?

24. How can huge cargo ships carry dense iron ore across the Great Lakes from the mines of Minnesota to various steel makers spread across the Midwest without the ships sinking from the weight of their loads? Why does such a ship ride higher in the water when empty?

25. Compare your ability to float in a very salty sea, such as the Great Salt Lake or the Dead Sea, to your ability to float in a fresh-water lake.

26. How does a baseball pitcher throw a curve ball? Explain how a ball curves in terms of the principles discussed in this chapter.

27. A fixed amount of helium gas is held inside a 1-liter container at a temperature of 25°C and atmospheric pressure. If the container expands to 2 liters without any change in temperature or amount of gas, what happens to the pressure and why?

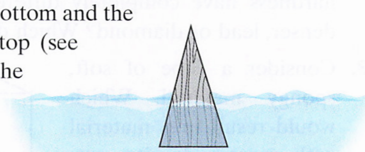
28. Diamond is a hard transparent material made of only carbon atoms. Graphite is a black, soft material used to make pencil lead and is made of only carbon atoms. However, graphite and diamond have different densities. Explain how two materials made of identical atoms can have different densities.

29. In one scene in the movie *The Godfather II,* a solid gold phone is passed around a large table for everyone to see. Suppose the volume of gold in the phone was equal to the volume of a 10-centimeter cube of gold. Do you think such a phone could be casually passed around a table from hand to hand? Explain. (*Hint:* A 10-centimeter cube is 1 thousandth of a cubic meter. Look up the density of gold in Table 10-1.)

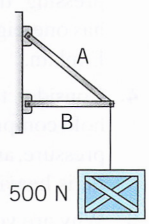
30. Helga says that although it's impossible to walk on a sea of water, it is possible to walk on a sea of mercury. She claims that if you step into a pool of mercury, you will only sink enough so that about half of your calf muscle is submerged. Ali disagrees with her statement. Who is right, Helga or Ali? Explain.

31. If you increase the temperature of a closed container of gas that has a fixed volume, the pressure inside will increase. The pressure on the walls of the container is due to the collisions of the gas molecules with the container wall. What must be happening to the gas molecules as the temperature is raised for them to exert a greater force on the walls?

32. A wedge-shaped piece of wood is floating in water with the widest part on the bottom and the narrowest part on top (see figure). If we want the wood to displace the least amount of water, should we leave it as is, should we turn it over, or doesn't it matter? Explain.



33. A 500-newton crate hangs from support beams as shown in the figure. State whether each beam is under compression or tension.



34. Suppose a small cube-shaped building is 10 meters on a side. What is the volume of this building? If it has a flat roof, what is the surface area of the five sides exposed to the outside? Answer the same questions for a building that is 5 meters on a side. Which building has a larger surface area to volume ratio? (The surface area to volume ratio is the surface area divided by the volume.)

35. Large things tend to have less surface area compared to their volume. Based on this fact, who is more likely to get cold in the winter, a fully grown man or a small child? Which is cheaper to heat in the winter, a single-family home or a living unit of the same size that is part of a large apartment building?

36. The average two-year-old boy is 36 inches (3 feet) tall and weighs 30 pounds. Suppose that when he is fully grown, he is 6 feet tall. If the rules of scaling apply, how much will he weigh when he is fully grown? Do you scaling apply to growing humans?

Problem-Solving Examples

EXAMPLE 10-2 High-Pressure Footwear

A woman with a mass of 50 kg wears shoes with high heels. The square heels measure 0.5 cm on a side. At one point during her stride, all of her weight is on one heel. What is the pressure on the floor at that point?

SOLUTION: Pressure (in pascals, or newtons per square meter) equals force divided by area. The area of the heel is

$$A = 0.5 \text{ cm} \times 0.5 \text{ cm} = 0.25 \text{ cm}^2 = 2.5 \times 10^{-5} \text{ m}^2$$

The force exerted is her weight, which is

$$F = m \times g = 50 \text{ kg} \times 9.8 \text{ m/s}^2 = 490 \text{ N}$$

This means that the pressure is

$$P = \frac{F}{A} = \frac{490 \text{ N}}{2.5 \times 10^{-5} \text{ m}^2} = 2.0 \times 10^7 \text{ Pa}$$

This is a very high pressure, equal to about 3000 psi of floor. Even though the woman's weight is modest, the fact that it is applied over a small area means that the pressure is large. Engineers who design flooring materials know that they have to take effects like this into account so that high-heeled shoes don't damage the floor. ●

EXAMPLE 10-3 A Moving Air Parcel

The term "parcel" is used by meteorologists to refer to a volume of air with the same pressure and temperature throughout. Suppose a 1000-liter parcel of air at 1 atmosphere pressure and a temperature of 30°C rises up along the side of a mountain range. At the top, the pressure is now 0.75 atmosphere and the temperature is −10°C (cold enough for snow). What is the new volume of the parcel?

REASONING AND SOLUTION: Both the pressure and temperature have changed, so we need to use the ideal gas law for a fixed amount of gas. Remember that we have to use temperature in kelvins, so we first convert the given temperatures. The initial temperature is

$$T \text{ (in K)} = T \text{ (in °C)} + 273 = 30 + 273 = 303 \text{ K}$$

The final temperature is

$$T \text{ (in K)} = T \text{ (in °C)} + 273 = -10 + 273 = 263 \text{ K}$$

We solve the ideal gas law equation for the final volume, V_2, and then substitute the given data:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$V_2 = V_1 \times \frac{P_1}{P_2} \times \frac{T_2}{T_1} = 1000 \text{ L} \times \frac{1 \text{ atm}}{0.75 \text{ atm}} \times \frac{263 \text{ K}}{303 \text{ K}} = 1157 \text{ L}$$

The decrease in pressure more than offset the decrease in temperature, and the air has expanded. ●

Problems

1. What is the weight of a column of water 5 feet high with a radius of 1 meter?

2. A perfectly spherical piece of metal is found at the bottom of a wishing well. If the mass of the object is 0.45 kg and the radius is 0.12 m, what is its density? If this object is pure gold, what is its mass? How much does it weigh?

3. Martin finds a piece of metal in a scrap yard and weighs it. Its mass is found to be 4740 kg and its volume is determined by immersion in water to be 0.6 cubic meters. What is the likely identity of this metal? What would the volume of the scrap metal be if it had the same weight and were made of lead?

4. A water holding tank measures 100 m long, 45 m wide, and 10 m deep. Traces of mercury have been found in the tank, with a concentration of 60 mg/L. What is the total mass of mercury in the tank?

5. What is the mass of water required to fill a circular hot tub 3 meters in diameter and 1.5 meters deep? Do you think this will require special reinforcement of the floors if placed on the second floor?

6. A medic applies a force of 85 newtons to a 0.03-square-meter area that is bleeding. What is the pressure in pascals that she applies? What is the pressure in pounds per square inch? Is this a lot or just a little bit of pressure?

7. How much pressure in pascals is applied to the ground by a 104-kg man who is standing on square stilts that measure 0.05-m on each edge? How much pressure is this in pounds per square inch?

8. A column of water has a diameter of 2 meters and a depth of 10 meters.
   a. How much pressure in pascals is there at the bottom of the column?
   b. What is the weight of this column of water?
   c. What is the pressure if the column has a radius of 6 m? If it has a depth of 15 m?
   d. In what direction does this calculated pressure exist?

9. A dense plastic toy of mass 3 kg is floating just beneath the surface of a pond. What is the buoyant force on it?

10. A 2×4 (a piece of wood about 2 inches thick and 4 inches wide) from a nearby construction site floats near the shore of a lake. If it is floating in very calm water with half of its volume submerged and the other half of its volume just above the surface, what is the density of this 2×4? (Density of water = $1 g/cm^3$)

Investigations

1. Research the development of the modern submarine. How does a submarine control its buoyancy and hence its depth?

2. Often, local gyms and health clinics offer a body fat analysis in which they weigh you in water to get an estimate of your percentage of body fat. If you can, have this done to see what your percentage of body fat is. How does this method work? What is the procedure used and what principles explored in this chapter are fundamental to this technique?

3. Explore the problem of lift in airplanes. How did early airplane designers develop a wing that provided sufficient lift? What were some of the problems encountered and how were they solved?

4. Visit a construction site if you are able to and investigate what different types of materials are used and why they are used. What is built from concrete, what is built from steel and other metals and alloys, and what is built from wood and synthetic materials? How do the properties of these materials studied in this chapter affect their use? What are the trade-offs involved in terms of strength, cost, weight, and so forth, for the various materials you can see?

5. The *Alvin* was one of the first successful deep-sea diving submarines, exploring some of the deepest trenches in the Pacific. Investigate what were some of the obstacles in designing a vessel to withstand such depths. What materials were used to create a hull that was strong enough to withstand the pressure of the deepest trenches without being so heavy as to sink?

6. Muscles are remarkable for their elasticity. Use the Internet to investigate the biological materials that make up muscle fibers. What triggers muscle contractions? What physical changes do muscle materials undergo during this process?

7. Occasionally, large dams collapse, sometimes with catastrophic loss of life and property. Investigate the history of one such accident. What caused the dam to fail? What maintenance is required to keep the largest dams safe?

8. Investigate the design of a hydraulic lift near where you live or work. (You might find one as part of an elevator, at a service station, or on a piece of construction equipment). What fluid is used? How is the pressure generated? How much weight can it lift?

WWW Resources

See the *Physics Matters* home page at **www.wiley.com/college/trefil** for valuable web links.

1. **http://www.uncwil.edu/nurc/aquarius/lessons/buoyancy.htm** Simple lessons and activities regarding buoyancy and pressure, part of the physics of diving..
2. **http://www.walter-fendt.de/ph14e/buoyforce.htm** A Java applet for conducting a simple experiment for calculating the buoyant force applied to an object immersed in a liquid.
3. **http://www.walter-fendt.de/ph14e/hydrostpr.htm** A Java applet for conducting a simple experiment measuring hydrostatic pressure in liquids.
4. **http://www.allstar.fiu.edu/aero/Experiment1.htm** An experiment demonstrating the Bernoulli's effect.
5. **http://webphysics.ph.msstate.edu/javamirror/ntnujava/idealGas/idealGas.html** A Java applet simulating the relation between density, pressure, and partial velocity for an ideal gas.
6. **http://www.history.rochester.edu/steam/hero/** The "Pneumatics" of Hero of Alexandria, an ancient scientific treatise translated from the ancient Greek.
7. **http://zebu.uoregon.edu/nsf/piston.html** A simulation of the relationship between an ideal gas and pressure.

36. The average two-year-old boy is 36 inches (3 feet) tall and weighs 30 pounds. Suppose that when he is fully grown, he is 6 feet tall. If the rules of scaling apply, how much will he weigh when he is fully grown? Do you think the rules of scaling apply to growing humans?

Problem-Solving Examples

EXAMPLE 10-2 High-Pressure Footwear

A woman with a mass of 50 kg wears shoes with high heels. The square heels measure 0.5 cm on a side. At one point during her stride, all of her weight is on one heel. What is the pressure on the floor at that point?

SOLUTION: Pressure (in pascals, or newtons per square meter) equals force divided by area. The area of the heel is

$$\begin{aligned} A &= 0.5 \text{ cm} \times 0.5 \text{ cm} \\ &= 0.25 \text{ cm}^2 \\ &= 2.5 \times 10^{-5} \text{ m}^2 \end{aligned}$$

The force exerted is her weight, which is

$$\begin{aligned} F &= m \times g \\ &= 50 \text{ kg} \times 9.8 \text{ m/s}^2 \\ &= 490 \text{ N} \end{aligned}$$

This means that the pressure is

$$\begin{aligned} P &= \frac{F}{A} \\ &= \frac{490 \text{ N}}{2.5 \times 10^{-5} \text{ m}^2} \\ &= 2.0 \times 10^7 \text{ Pa} \end{aligned}$$

This is a very high pressure, equal to about 3000 psi of floor. Even though the woman's weight is modest, the fact that it is applied over a small area means that the pressure is large. Engineers who design flooring materials know that they have to take effects like this into account so that high-heeled shoes don't damage the floor. ●

EXAMPLE 10-3 A Moving Air Parcel

The term "parcel" is used by meteorologists to refer to a volume of air with the same pressure and temperature throughout. Suppose a 1000-liter parcel of air at 1 atmosphere pressure and a temperature of 30°C rises up along the side of a mountain range. At the top, the pressure is now 0.75 atmosphere and the temperature is −10°C (cold enough for snow). What is the new volume of the parcel?

REASONING AND SOLUTION: Both the pressure and temperature have changed, so we need to use the ideal gas law for a fixed amount of gas. Remember that we have to use temperature in kelvins, so we first convert the given temperatures. The initial temperature is

$$T \text{ (in K)} = T \text{ (in °C)} + 273 = 30 + 273 = 303 \text{ K}$$

The final temperature is

$$T \text{ (in K)} = T \text{ (in °C)} + 273 = -10 + 273 = 263 \text{ K}$$

We solve the ideal gas law equation for the final volume, V_2, and then substitute the given data:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$\begin{aligned} V_2 &= V_1 \times \frac{P_1}{P_2} \times \frac{T_2}{T_1} \\ &= 1000 \text{ L} \times \frac{1 \text{ atm}}{0.75 \text{ atm}} \times \frac{263 \text{ K}}{303 \text{ K}} \\ &= 1157 \text{ L} \end{aligned}$$

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