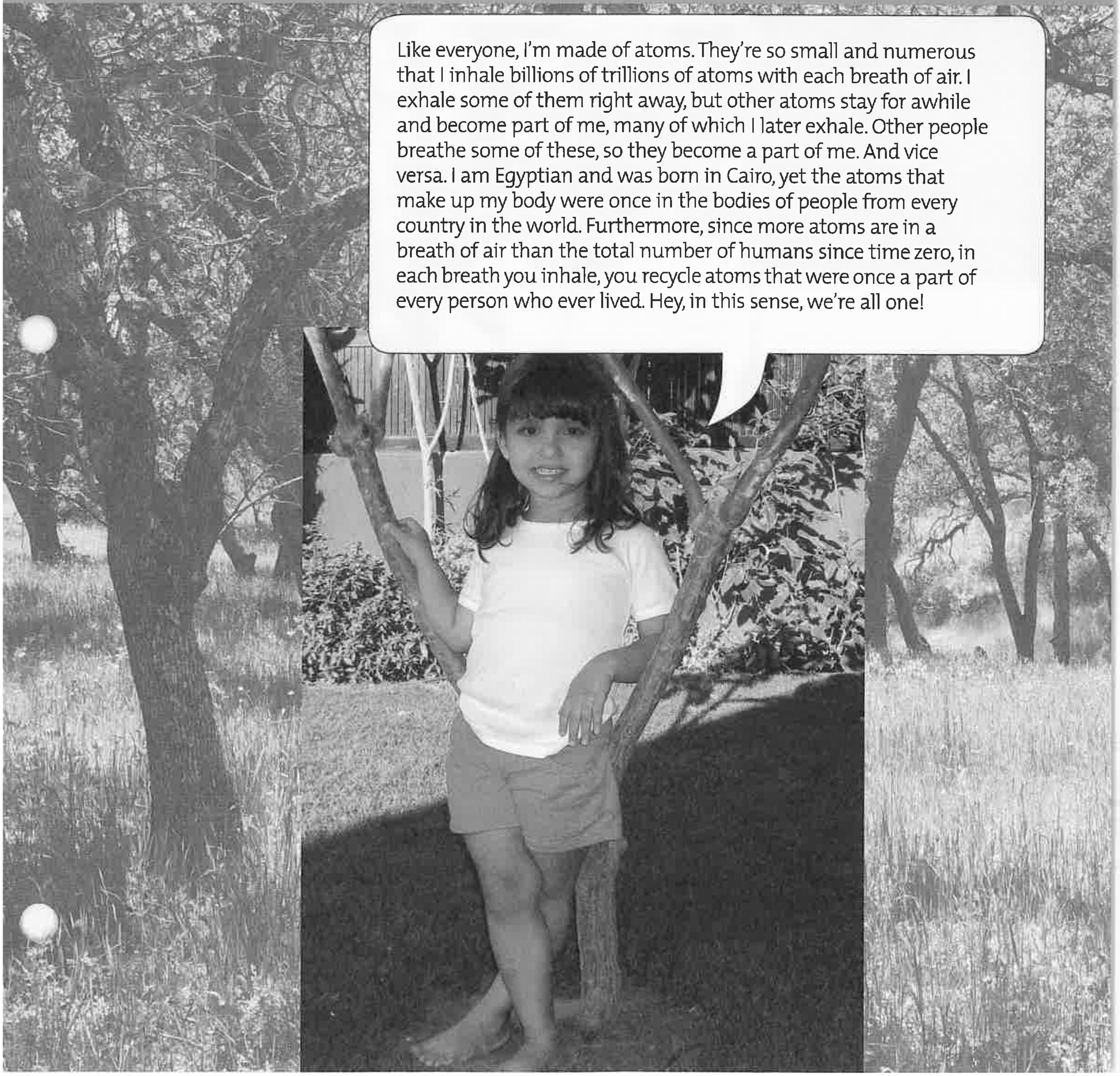
Part Two

Properties of Matter



Like everyone, I'm made of atoms. They're so small and numerous that I inhale billions of trillions of atoms with each breath of air. I exhale some of them right away, but other atoms stay for awhile and become part of me, many of which I later exhale. Other people breathe some of these, so they become a part of me. And vice versa. I am Egyptian and was born in Cairo, yet the atoms that make up my body were once in the bodies of people from every country in the world. Furthermore, since more atoms are in a breath of air than the total number of humans since time zero, in each breath you inhale, you recycle atoms that were once a part of every person who ever lived. Hey, in this sense, we're all one!

11 The Atomic Nature of Matter

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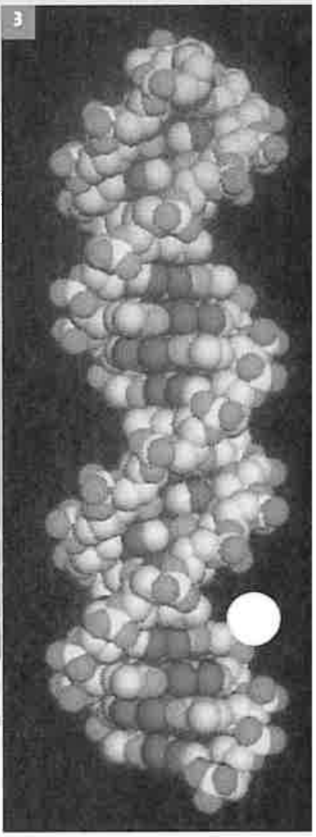

1 An artist's rendition of the tip of a scanning probe microscope (SPM), which maps out the relative positions of atoms on the surface of a material. The tip can also be used to move individual atoms around as desired or to sketch patterns, such as those needed for ultra small integrated circuits. 2 Extraordinary 20th-century physicist Richard P. Feynman. 3 A depiction of a DNA molecule, the stuff of life.

Most people, when asked who was the most outstanding physicist of the 20th century, are likely to answer Albert Einstein. When physicists are asked who was the most playful and colorful physicist of the 20th century, if their answer isn't Einstein, it's likely to be Richard Feynman. This chapter is about atoms, the focus of Feynman's work and teaching that led to our further understanding of the atom, and a Nobel Prize in Physics for him. If you read his book *Surely You're Joking, Mr. Feynman,* you will see that in addition to his love of physics, he was very much interested in how physics is taught—particularly in high school. I was privileged to be on a panel of teachers with Feynman at a meeting of physics educators in 1987. The panel addressed the question of what kind of physics should be taught in high school. When I arrived at the school where the meeting was held, I spotted Feynman standing in the hall, alone. It was known that Feynman was often alone at such meetings, for teachers were uncomfortable in his presence. What do you talk about to someone like Feynman? I had something to talk about because he had been sent a copy of my brand-new high school version of *Conceptual Physics,* and I wanted his impression of it. To my delight, but not to my surprise, he had read it—all of it, judging by his recommended improvements for the next edition. As his own *Joking* book makes

clear, Feynman "did his homework" before giving his presentations. He had read my book and several other high school books in preparation for this panel, which, sadly, was his last public appearance. We all knew he was fighting cancer.

On the panel I was almost flabbergasted to realize he and I were debating not how physics should be taught in high schools but rather whether it should be taught at all. Feynman liked extreme points of view, and his position was that it shouldn't be taught in high school because most of the teachers lacked a passion for the subject. This lack of passion would be communicated to students, who would be better off arriving at college with a clean slate. My position was that physics should be taught conceptually, with any problem-solving course as a second course in physics—that the central concepts of physics should be familiar to all students—that physics, like math and English and history, should be in the educational mainstream. Feynman countered that a major problem with my position was the inadequate number of trained physics teachers. Where would they come from? My reply was that if we made the course delightful, more than the current percentage of students would like physics, then major in it, and in 10 years be in the ranks of needed teachers.

Ten years later at a physics meeting in Las Vegas, a young man stopped me in the hall to tell me how his encounter with my book steered him to majoring in physics and then becoming a physics teacher. He further expressed a passion for physics. I thought to myself, "Did you hear that, Richard?" For it was true, the conceptual orientation of physics helped increase the ranks of new physics teachers. My motto since has been that, if a learner's first course in physics is delightful, the rigor of a second course will be welcomed.

The Atomic Hypothesis

The idea that matter is composed of atoms goes back to the Greeks in the 5th century BC. Investigators of nature back then wondered whether matter was continuous or not. We can break a rock into pebbles, and the pebbles into fine gravel. The gravel can be broken into fine sand, which then can be pulverized into powder. To the 5th-century Greeks, there was a smallest bit of rock, an "atom," that could not be divided any further.

Aristotle, the most famous of the early Greek philosophers, didn't agree with the idea of atoms. In the 4th century BC, he taught that all matter is composed of various combinations of four elements—earth, air, fire, and water. This view seemed reasonable because, in the world around us, matter is seen in only four forms: solids (earth), gases (air), liquids (water), and the state of flames (fire). The Greeks viewed

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- If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence could be passed on to the next generation of creatures, Richard Feynman chose this: "All things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another." The idea that matter is composed of atoms is a central foundation of all of science.

Falling Alice

Imagine that you inhabit the world of Alice in Wonderland when she shrank in size. Pretend that you topple from a chair and fall in slow motion to the floor—and while falling, you continually shrink. You brace yourself for impact on the wood floor; and, as you get nearer and nearer, becoming smaller and smaller, you notice that the surface of the floor is not as smooth as it first looked. Great crevices appear that are the microscopic irregularities that are found in all wood. In falling into one of these canyon-sized crevices, you again brace yourself for impact, only to find that the bottom of the canyon consists of many other crevices. Falling farther while growing even smaller, you notice the solid walls throb and pucker. The throbbing surfaces consist of hazy blobs, mostly spherical, some egg-shaped, some larger than others, and all oozing into each other, forming long chains of complicated structures. Falling still farther, you brace for impact as you approach one of these cloudy spheres, closer and closer, smaller and smaller, and—Wow! You have entered what seems to be a new universe. You fall into a sea of emptiness, occupied by occasional specks whirling past at unbelievably high speeds. You are in an *atom*, as empty of matter as the solar system. The solid floor you have fallen into is, except for specks of matter here and there, mostly empty space. You have entered the world of the atom.

fire as the element of change, since fire was observed to produce changes on substances that burned. Aristotle's ideas about the nature of matter persisted for more than 2000 years.

The atomic idea was revived in the early 1800s by an English meteorologist and school teacher, John Dalton. He successfully explained the nature of chemical reactions by proposing that all matter is made of atoms. He and others of the time, however, had no direct evidence for their existence. Then, in 1827, a Scottish botanist named Robert Brown noticed something very unusual in his microscope. He was studying grains of pollen suspended in water, and he saw that the grains were continually moving and jumping about. At first he thought the grains were some kind of moving life forms, but later he found that dust particles and grains of soot suspended in water moved in the same way. This perpetual and haphazard jiggling of tiny particles—now called **Brownian motion**—results from collisions between visible particles and invisible atoms. The atoms are invisible because they're so small. Although he couldn't see the atoms, Brown could see the effect they had on particles he *could* see. It's like a supergiant beach ball being bounced around by a crowd of people at a football game. From a high-flying airplane, you wouldn't see the people because they are small relative to the enormous ball, which you would be able to see. The pollen grains that Brown observed moved because they were constantly being jostled by the atoms (actually, by the atomic combinations referred to as molecules) that made up the water surrounding them.

Brownian motion was explained in 1905 by Albert Einstein, the same year that he announced the theory of special relativity. Until Einstein's explanation—which made it possible to find the masses of atoms—many prominent physicists remained skeptical about the existence of atoms. So we see that the reality of the atom was not firmly established until the early 20th century.

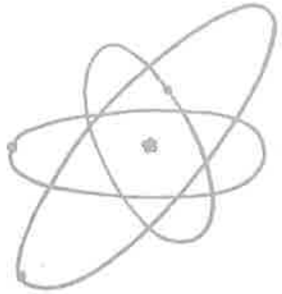

FIGURE 11.1
An early model of the atom, with a central nucleus and orbiting electrons, much like a solar system with orbiting planets.

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Video
Evidence for Atoms

We can't see atoms because they're too small. We can't see the farthest star either. There's much that we can't see with our eyes. But that doesn't prevent investigation of such things so that we can "see" them via our instruments.

Characteristics of Atoms

Atoms Are Incredibly Tiny An atom is as many times smaller than you as an average star is larger than you. A nice way to say this is that we stand between the atoms and the stars. Or another way of stating the smallness of atoms is that the diameter of an atom is to the diameter of an apple as the diameter of an apple is to the diameter of Earth. So, to imagine an apple full of atoms, think of the Earth solid-packed with apples. Both have about the same number.

Atoms Are Numerous There are about 100,000,000,000,000,000,000,000 atoms in a gram of water (a thimbleful). In scientific notation, that's 10^{23} atoms. The number 10^{23} is an enormous number, more than the number of drops of water in all the lakes and rivers of the world. So there are more atoms in a thimbleful of water than there are drops of water in the world's lakes and rivers. In the atmosphere, there are about 10^{22} atoms in a liter of air. Interestingly, the volume of the atmosphere contains about 10^{22} liters of air. That's an incredibly large number of atoms, and the same incredibly large number of liters of atmosphere. Atoms are so small and so numerous that there are about as many atoms in the air in your lungs at any moment as there are breathfuls of air in Earth's atmosphere.

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- How long would it take you to count to 1 million? If each count takes 1 second, counting nonstop to a million would take 11.6 days. To count to a billion (10^9) would take 31.7 years. To count to a trillion (10^{12}) would take 31,700 years. Counting to 10^{22} would take more than 10,000 times the age of the universe!

Atoms Are Perpetually Moving In solids, they vibrate in place; in liquids, they migrate from one location to another; and in gases, the rate of migration is even greater. Drops of food coloring in a glass of water, for example, soon spread to color the entire glass of water. The same would be true of a cupful of food coloring thrown into an ocean: It would spread around and later be found in every part of the world's oceans.

Atoms and molecules in the atmosphere zip around at speeds up to 10 times the speed of sound. They spread rapidly, so some of the oxygen molecules you breathe may have been halfway across the country a few days ago. Taking Figure 11.2 further, your exhaled breaths of air quite soon mix with other atoms in the atmosphere. After the few years it takes for your breath to mix uniformly in the atmosphere, anyone, anywhere on Earth, who inhales a breath of air will take in, on the average, one of the atoms in that exhaled breath of yours. But you exhale many, many breaths, so other people breathe in many, many atoms that were once in your lungs—that were once a part of you; and, of course, vice versa. Believe it or not, with each breath you take in, you breathe atoms that were once a part of everyone who ever lived! Considering that the atoms we exhale were part of our bodies (the nose of a dog has no trouble discerning this), it can be truly said that we are literally breathing one another.

Smell discrimination for salmon has been measured in parts per *trillion*—quite incredible. When the time comes to return from the ocean to their original habitat, salmon follow their noses. They swim in a direction where concentrations of familiar water become greater. In time, they encounter the source of that water where they spent the first 2 years of their lives.

Atoms Are Ageless Many atoms in your body are nearly as old as the universe itself. When you breathe, for example, only some of the atoms that you inhale are exhaled in your next breath. The remaining atoms are taken into your body to become part of you, and they later leave your body by various means. You don't "own" the atoms that make up your body; you borrow them. We all share from the same atom pool, as atoms forever migrate around, within, and among us. Atoms cycle from person to person as we breathe and as our perspiration is vaporized. We recycle atoms on a grand scale.

The origin of the lightest atoms goes back to the origin of the universe, and most heavier atoms are older than the Sun and Earth. There are atoms in your body that have existed since the first moments of time, recycling throughout the universe among innumerable forms, both nonliving and living. You're the present caretaker of the atoms in your body. There will be many who will follow you.

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Video
Atoms Are Recyclable

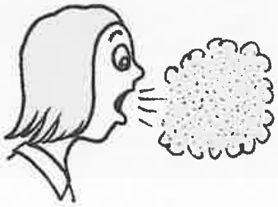

FIGURE 11.2
There are as many atoms in a normal breath of air as there are breathfuls of air in Earth's atmosphere.

CHECK POINT

1. Which are older, the atoms in the body of an elderly person or those in the body of a baby?
2. World population grows each year. Does this mean that the mass of Earth increases each year?
3. Are there really atoms that were once a part of Albert Einstein incorporated in the brains of all the members of your family?

Check Your Answers

1. The age of the atoms in both is the same. Most of the atoms were manufactured in stars that exploded before the solar system came into existence.
2. The greater number of people increases the mass of Earth by zero. The atoms that make up our bodies are the same atoms that were here before we were born—we are but dust, and unto dust we shall return. The materials that make up human cells are rearrangements of material already present. The atoms that make up a baby forming in its mother's womb are supplied by the food the mother eats. And those atoms originated in stars—some of them in far-away galaxies. (Interestingly, the mass of Earth *does* increase by the incidence of roughly 40,000 tons of interplanetary dust each year, but not by the birth and survival of more people.)
3. Quite so, and of Barack Obama too. However, these atoms are combined differently than they were previously. If you experience one of those days when you feel like you'll never amount to anything, take comfort in the thought that many of the atoms that now constitute your body will live forever in the bodies of all the people on Earth who are yet to be. Our atoms are immortal.

Life is not measured by the number of breaths we take, but by the moments that take our breath away. —*George Carlin*

Atomic Imagery

Atoms are too small to be seen with visible light. Because of diffraction, you can discern details no smaller than the wavelength of light you use to look with. This can be understood by an analogy with water waves. A ship is much larger than the water waves that roll on by it. As Figure 11.3 shows, water waves can reveal features of the ship. The waves *diffract* as they pass the ship. But diffraction is nil for waves that pass by the anchor chain, revealing little or nothing about it. Similarly, waves of visible light are too coarse compared with the size of an atom to show details of atomic size and shape.

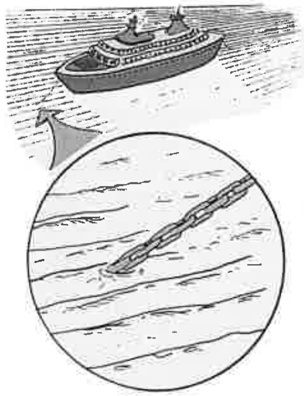

FIGURE 11.3
Information about the ship is revealed by passing waves because the distance between wave crests is small compared with the size of the ship. The passing waves reveal nothing about the chain.

Yet here in Figure 11.4 we see a picture of atoms—the historic 1970 image of chains of individual thorium atoms. The picture is not a photograph but an electron micrograph—it was not made with light but with a thin electron beam in a scanning electron microscope (SEM) developed by Albert Crewe at the University of Chicago's Enrico Fermi Institute. An electron beam, such as the one that sprays a picture on an early television screen, is a stream of particles that have wave properties. The wavelength of an electron beam is smaller than the wavelengths of visible light, and atoms are larger than the tiny wavelengths of an electron beam. Crewe's electron micrograph is the first high-resolution image of individual atoms.

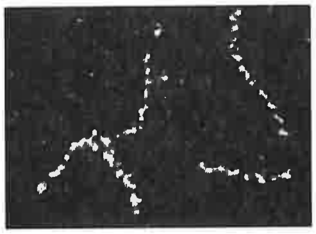

FIGURE 11.4
The strings of dots are chains of thorium atoms imaged with a scanning electron microscope. This historic photograph of individual atoms was taken in 1970 by researchers at the University of Chicago's Enrico Fermi Institute.

In the mid-1980s, researchers developed a new kind of microscope—the scanning tunneling microscope (STM). It employs a sharp tip that is scanned over a surface at a distance of a few atomic diameters in a point-by-point and line-by-line fashion. At each point, a tiny electric current, called a tunneling current, is measured between the tip and the surface. Variations in the current reveal the surface topology. The image of Figure 11.5 beautifully shows the position of a ring of atoms. The ripples shown in the ring reveal the wave nature of matter. This image, among many others, underscores the delightful interplay of art and science.

Sometimes a model is useful even when it's incorrect. Scotsman James Watt constructed a workable steam engine in the 18th century based on a model of heat that turned out to be quite incorrect.

Because we can't see inside an atom, we construct models. A model is an abstraction that helps us to visualize what we can't see, and, importantly, it enables us to make predictions about unseen portions of the natural world. An early model of the atom (and the one most familiar to the general public) is akin to that of the solar system. As with the solar system, most of an atom's volume is empty space. At the center is a tiny and very dense nucleus in which most of the mass is concentrated. Surrounding the nucleus are "shells" of orbiting particles. These are **electrons,** electrically charged basic units of matter (the same electrons that constitute the electric current in your iPhone). Although electrons electrically repel other electrons, they are electrically attracted to the nucleus, which has a positive charge. As the size and charge of the nuclei increase, electrons are pulled closer, and the shells become smaller. Interestingly, the uranium atom, with its 92 electrons, is not appreciably larger in diameter than the lightest atom, hydrogen. This model was first proposed in the early 20th century, and it reflects a rather simplified understanding of the atom. It was soon discovered, for example, that electrons don't orbit the atom's

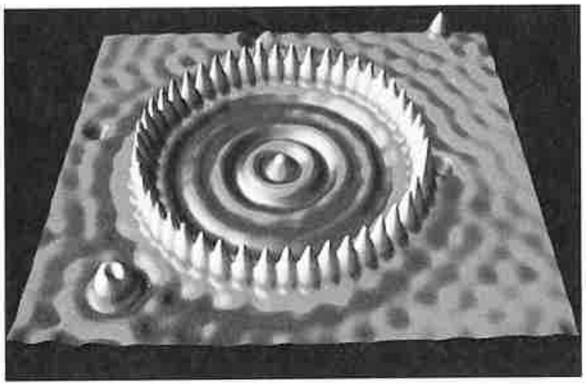

FIGURE 11.5
An image of 48 iron atoms positioned into a circular ring that "corrals" electrons on a copper crystal surface, taken with a scanning tunneling microscope at the IBM Almaden Laboratory in San Jose, California.

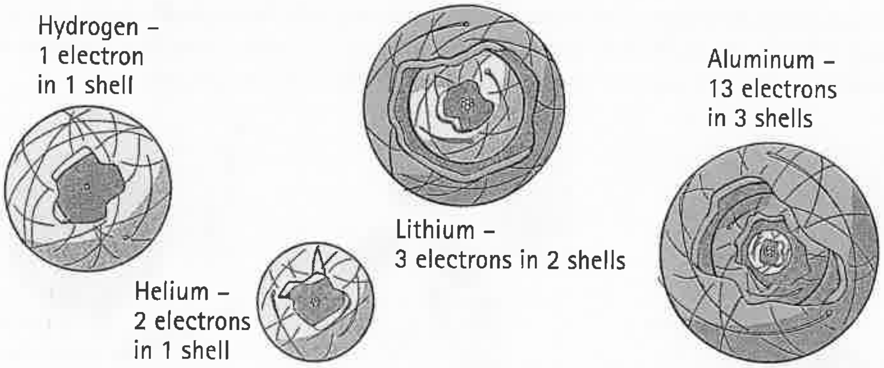

FIGURE 11.6
A simplified model of the atom consists of a tiny nucleus surrounded by electrons that orbit in shells. As the charges of nuclei increase, electrons are pulled closer, and the shells become smaller.

center like planets orbit the Sun. Like most early models, however, the planetary atomic model served as a useful stepping stone to further understanding and more accurate models. Any atomic model, no matter how refined, is nothing more than a symbolic representation of the atom and not a physical picture of the actual atom.

Artists and scientists both look for patterns in nature, finding connections that have always been there yet have missed the eye.

Atomic Structure

Nearly all the mass of an atom is concentrated in the **atomic nucleus,** which occupies only a few quadrillionths of its volume. The nucleus, therefore, is extremely dense. If bare atomic nuclei could be packed against each other into a lump 1 centimeter in diameter (about the size of a large pea), the lump would weigh 133,000,000 tons! Huge electrical forces of repulsion prevent such close packing of atomic nuclei because each nucleus is electrically charged and repels all other nuclei. Only under special circumstances are the nuclei of two or more atoms squashed into contact. It can happen when nuclei in a laboratory are slammed into a target, or when matter is heated to millions of degrees. A nuclear reaction resulting from high temperature is called a *thermonuclear fusion reaction.* It occurs in the centers of stars and ultimately makes them shine. (We'll discuss these nuclear reactions in Chapter 34.)

The principal building block of the nucleus is the *nucleon,* which is in turn composed of fundamental particles called *quarks.* When a nucleon is in an electrically neutral state, it is a *neutron;* when it is in a positively charged state, it is a **proton.** All protons are identical; they are copies of one another. Likewise with neutrons: Each neutron is like every other neutron. The lighter nuclei have roughly equal numbers of protons and neutrons; more massive nuclei have more neutrons than protons. Protons have a positive electric charge that repels other positive charges but attracts negative charges. So like kinds of electrical charges repel one another, and unlike charges attract one another. It is the positive protons in the nucleus that attract a surrounding cloud of negatively charged electrons to constitute an atom. (The strong nuclear force, which binds the protons to neutrons and to each other within the nucleus, is described in Chapter 33.)

The Elements

When a substance is composed of only one kind of atom, we call that substance an **element.** The words *element* and *atom* are often used in a similar context, the distinction being that elements are made of atoms and not the other way around. A pure 24-carat gold ring, for example, is composed only of gold atoms. A gold ring with a lower carat value is composed of gold and other elements, such as nickel. The silvery liquid in a barometer or thermometer is the element mercury. The entire liquid consists of only mercury atoms. An atom of a particular element is the smallest sample of that element. Although atom and element are often used interchangeably,

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- A combination of 26 letters makes up every word in the English language. Similarly, all material things in the world are composed of different combinations of about 100 different elements.

element refers to a type of substance (one containing only one type of atom), whereas atom refers to the individual particles that make up that substance. For example, we speak of isolating a mercury *atom* from a flask of the *element* mercury.

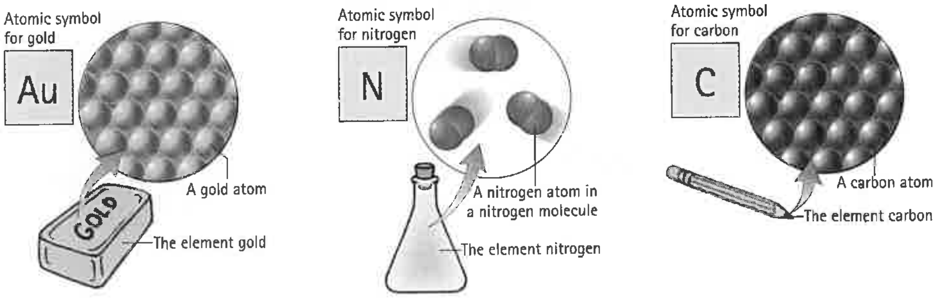

FIGURE 11.7

Any element consists only of one kind of atom. Gold consists only of gold atoms, a flask of gaseous nitrogen consists only of nitrogen atoms, and the carbon of a graphite pencil is composed only of carbon atoms.

FIGURE 11.8

Both you and Leslie are made of stardust—in the sense that the carbon, oxygen, nitrogen, and other atoms that make up your body originated in the deep interiors of ancient stars that have long since exploded.

The lightest atom of all is that of hydrogen. In the universe at large, hydrogen is the most abundant element—more than 90% of the atoms are hydrogen atoms. Helium, the second-lightest element, provides most of the remaining atoms in the universe. Heavier atoms in our surroundings were manufactured by the fusion of light elements in the hot, high-pressure cauldrons deep within the interiors of stars. The heaviest elements form when huge stars implode and then explode—supernovas. Nearly all the elements on Earth are remnants of stars that exploded long before the solar system came into existence.

To date, more than 115 elements have been identified. Of these, about 90 occur in nature. The others are produced in the laboratory with high-energy atomic accelerators and nuclear reactors. These laboratory-produced elements are too unstable (radioactive) to occur naturally in appreciable quantities. From a pantry containing less than 100 elements, we have the atoms that constitute almost every simple, complex, living, or nonliving substance in the known universe. More than 99% of the material on Earth is formed from only about a dozen of the elements. The other elements are relatively rare. Living things are composed primarily of five elements: oxygen (O), carbon (C), hydrogen (H), nitrogen (N), and calcium (Ca). The letters in parentheses represent the chemical symbols for these elements.

The Periodic Table of the Elements

Elements are classified by the number of protons in their nucleus—their **atomic number.** Hydrogen, containing one proton per atom, has atomic number 1; helium, containing two protons per atom, has atomic number 2; and so on in sequence to the heaviest naturally occurring element, uranium, with atomic number 92. The numbers continue beyond atomic number 92 through the artificially produced transuranic (beyond uranium) elements. The arrangement of elements by their atomic numbers makes up the **periodic table of the elements** (Figure 11.9).

The periodic table is a chart that lists atoms by their atomic number and also by their electrical arrangements. It bears some resemblance to a calendar with its weeks in rows and its days in columns. From left to right, each element has atoms with one more proton and electron than the preceding element. Reading down the table, each element has atoms with one more shell than the one above. The inner shells are filled to their capacities, and the outer shell may or may not be, depending on the element. Only the elements at the far right of the table, where Saturdays would be on a calendar, have their outer shells filled to capacity. These are the *noble gases*—helium, neon,

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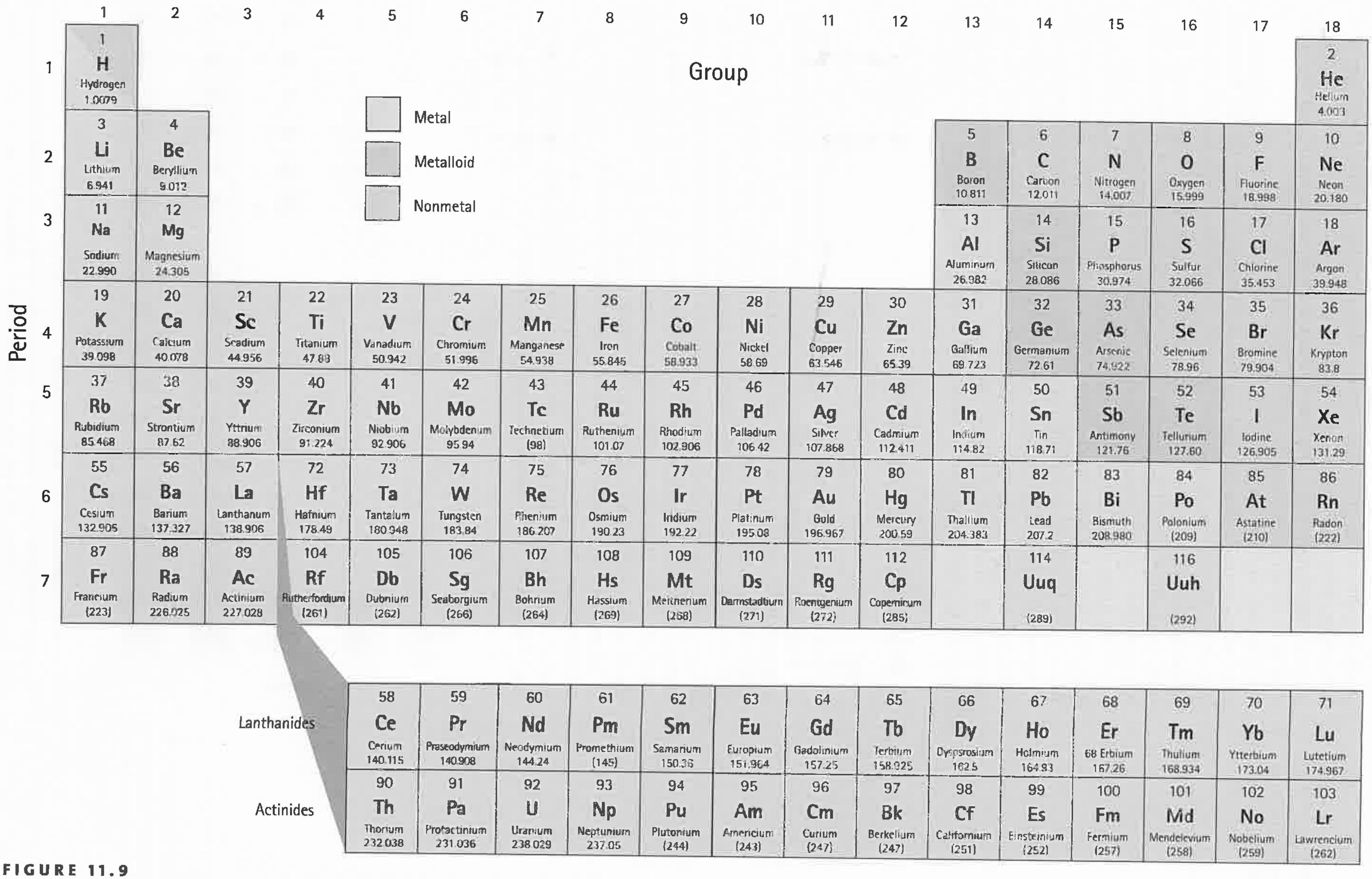
- Mercury, element number 80, is commonly found in rocks and minerals such as cinnabar ore and fossil fuels. Mercury on its own, undisturbed, is not harmful. But when ore is smashed or coal is burned, mercury is released into the air, where it can waft over hundreds of kilometers, depositing itself on trees and land or streams, lakes, and oceans. That is where it becomes a danger. When it combines with carbon it becomes methyl mercury, a deadly neurotoxin. Each year about 75 tons of mercury are in coal delivered to U.S. power plants and about $\frac{2}{3}$ of this is emitted to the air. China has now joined in this practice.



Group

Metal

Metalloid

Nonmetal

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen 1.0079																	2 He Helium 4.003
2	3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
3	11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scadium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.69	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.8
5	37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.60	53 I Iodine 126.905	54 Xe Xenon 131.29
6	55 Cs Cesium 132.905	56 Ba Barium 137.327	57 La Lanthanum 138.906	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Indium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
7	87 Fr Francium (223)	88 Ra Radium 226.025	89 Ac Actinium 227.028	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (269)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Cp Copernicum (285)		114 Uuq (289)		116 Uuh (292)		

Lanthanides	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.5	67 Ho Holmium 164.93	68 Er 68 Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinides	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.05	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

FIGURE 11.9

The periodic table of the elements. The number above the chemical symbol is the *atomic number*, and the number below is the *atomic mass* averaged by isotopic abundance in Earth's surface and expressed in atomic mass units (amu). Atomic masses for radioactive elements shown in parentheses are the whole number nearest the most stable isotope of that element.

Most of the elements of the periodic table are found in interstellar gases.

argon, krypton, xenon, and radon. The periodic table is the chemist's road map—and much more. Most scientists consider the periodic table to be the most elegant organizational chart ever devised. The enormous human effort and ingenuity that went into finding its regularities makes a fascinating atomic detective story.[1]

Elements may have up to seven shells, and each shell can hold some maximum number of electrons. The first and innermost shell has a capacity for two electrons and the second shell has a capacity for eight electrons. The arrangement of electrons in the shells dictates such properties as the melting and freezing temperatures, electrical conductivity, and the taste, texture, appearance, and color of substances. The arrangements of electrons quite literally give life and color to the world.

Models of the atom evolve with new findings. The old orbital model of the atom has given way to a model that views the electron as a standing wave—altogether different from the idea of an orbiting particle. This is the quantum mechanical model, introduced in the 1920s, which is a theory of the small-scale world that includes predicted wave properties of matter. It deals with "lumps" occurring at the subatomic level—lumps of matter or lumps of such things as energy and angular momentum. (More about the quantum in Chapter 31.)

Relative Sizes of Atoms

The diameters of the electron shells of atoms are determined by the amount of electrical charge in the nucleus. For example, the positive proton in the hydrogen atom holds one electron in an orbit at a certain radius. If we double the positive charge in the nucleus, the orbiting electron will be pulled into a tighter orbit with half its former radius, since the electrical attraction is doubled. This occurs for helium, which has a doubly charged nucleus when it attracts a single electron. Interestingly, an added second electron isn't pulled in as far because the first electron partially offsets the attraction of the doubly charged nucleus. This is a neutral helium atom, which is somewhat smaller than a hydrogen atom.

An atom with unbalanced electrical charge, for example a nucleus with more positive charge than the surrounding negative charges, is called an **ion.** An ion is a charged atom. A helium atom that holds only one electron, for example, is a helium ion. We say it is a positive ion because it has more positive charge than negative charge.

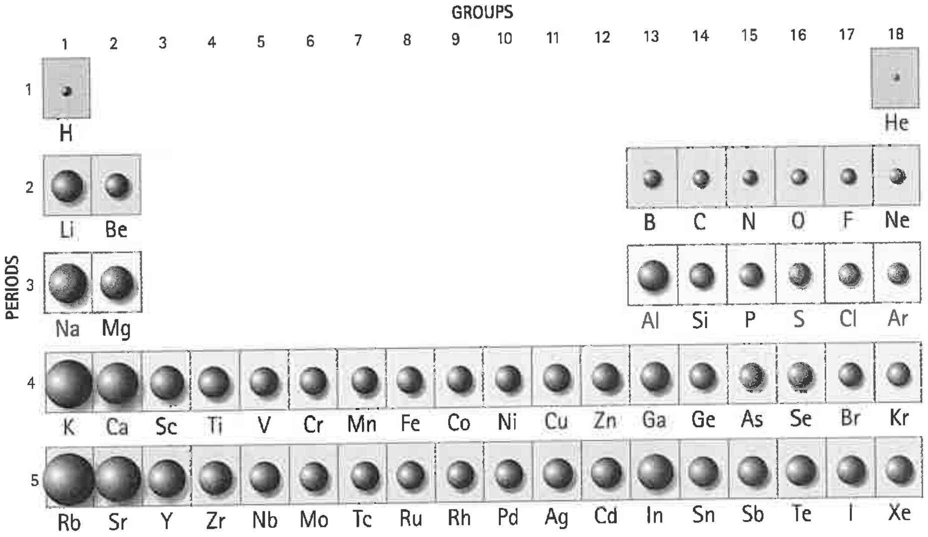


FIGURE 11.10

The sizes of atoms gradually decrease from left to right across the periodic table (only the first five periods are shown here).

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[1] The periodic table is credited to Russian chemistry professor Dmitri Mendeleev (1834–1907), who, most importantly, predicted with his table the existence of elements not then known. Mendeleev was a much loved and devoted teacher whose lecture halls were filled by students wanting to hear him speak. He was both a great teacher and a great scientist. Element 101 is named in his honor.

So two electrons around a doubly charged nucleus assume a configuration characteristic of helium. Two electrons surrounding a helium nucleus constitute a neutral atom. A third proton in an atomic nucleus can pull two electrons into an even closer orbit and, furthermore, hold a third electron in a somewhat larger orbit. This is the lithium atom, atomic number 3. We can continue with this process, increasing the positive charge of the nucleus and adding successively more electrons and more orbits all the way up to atomic numbers above 100, to the "synthetic" radioactive elements.[2]

We find that as the nuclear charge increases and additional electrons are added in outer orbits, the inner orbits shrink in size because of the stronger nuclear attraction. This means that the heavier elements are not much larger in diameter than the lighter elements. The diameter of the xenon atom, for example, is only about four helium diameters, even though it is nearly 33 times as massive. The relative sizes of atoms in Figure 11.10 are approximately to the same scale.

CHECK POINT

What fundamental force dictates the size of an atom?

Check Your Answer

The electrical force.

Isotopes

Whereas the number of protons in a nucleus exactly matches the number of electrons around the nucleus in a neutral atom, the number of protons in the nucleus need not match the number of neutrons there. For example, most iron nuclei with 26 protons contain 30 neutrons, while a small percentage contains 29 neutrons. Atoms of the same element that contain different numbers of neutrons are **isotopes** of the element. The various isotopes of an element all have the same number of electrons, and so, for the most part, they behave identically. We shall return to isotopes in Chapter 33.

We identify isotopes by their *mass number*, which is the total number of protons and neutrons (in other words, the number of nucleons) in the nucleus. A hydrogen isotope with one proton and no neutrons, for example, has a mass number of 1 and is referred to as hydrogen-1. Likewise, an iron atom with 26 protons and 30 neutrons has a mass number of 56 and is referred to as iron-56. An iron atom with 26 protons and only 29 neutrons is designated as iron-55.

The total mass of an atom is called its *atomic mass*. This is the sum of the masses of all the atom's components (electrons, protons, and neutrons). Because electrons are so much less massive than protons and neutrons, their contribution to atomic mass is negligible. Atoms are so small that expressing their masses in units of grams or kilograms is not practical. Instead, scientists use a specially defined unit of mass known as the **atomic mass unit** or **amu.** A nucleon has a mass of about 1 amu. The amu is defined as exactly 1/12 of the mass of a carbon-12 atom. The periodic table lists atomic masses in units of amu.

Don't confuse an isotope with an *ion*, which is an atom that is electrically charged owing to an excess or a deficiency of electrons.

Most elements have a variety of isotopes. The atomic mass for each element listed in the periodic table is the weighted average of the masses of these isotopes based on the occurrence of each isotope on Earth. For example, although the predominant isotope of carbon contains six protons and six neutrons, about 1% of all carbon atoms contain seven neutrons. The heavier isotope raises the average atomic mass of carbon from 12.000 amu to 12.011 amu.

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[2] Each orbit will hold only so many electrons. The numbers for the first four shells, for example, are 2, 8, 8, 18.

Don't confuse mass number with the atomic mass. *Mass number* is an integer that specifies an isotope and has no units—it's simply equal to the number of nucleons in a nucleus. *Atomic mass* is an average of the masses of isotopes of a given element, expressed in *atomic mass units* (amu).

CHECK POINT

1. Which contributes more to an atom's mass, electrons or protons? Which contributes more to an atom's volume (its size)?
2. Which is represented by a whole number—the mass number or the atomic mass?
3. Do two isotopes of iron have the same *atomic number?* The same *atomic mass number?*

Check Your Answers

1. Protons contribute more to an atom's mass; electrons contribute more to its size.
2. The mass number is always given as a whole number, such as hydrogen-1 or carbon-12. Atomic mass, by contrast, is the average mass of the various isotopes of an element and is thus represented by a fractional number.
3. The two isotopes of iron have the same atomic number 26, because they each have 26 protons in the nucleus. They have different atomic mass numbers if they have different numbers of neutrons in the nucleus.

Compounds and Mixtures

When atoms of different elements bond to one another, they make a **compound.** Examples of simple compounds include water, ammonia, and methane. A compound is uniquely different from the elements from which it is made, and it can only be separated into its constituent elements by chemical means. Sodium, for example, is a metal that reacts violently with water. Chlorine is a poisonous yellow-green gas. Yet the compound of these two elements is the harmless white crystal (NaCl) that you sprinkle on your potatoes. Consider also that, at ordinary temperatures, the elements hydrogen and oxygen are both gases. When combined, they form the compound water (H_2O), a liquid—quite different.

Not all substances react with one another chemically when they are brought close together. A substance that is mixed together without chemically bonding is called a **mixture.** Sand combined with salt is a mixture. Hydrogen and oxygen gas form a mixture until ignited, whereupon they form the compound water. A common mixture that we all depend on is nitrogen and oxygen together with a little argon and small amounts of carbon dioxide and other gases. It is the air that we breathe.

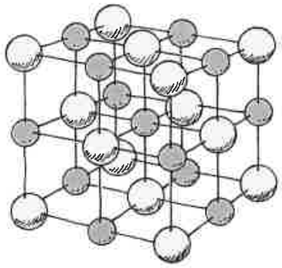


FIGURE 11.11
Table salt (NaCl) is a crystalline compound that is not made of molecules. The sodium (green) and chlorine (yellow) atoms comprise a crystal.

CHECK POINT

Is common table salt an element, a compound, or a mixture?

Check Your Answer

Salt is not an element, for if it were you'd see it listed in the periodic table. Pure table salt is a compound of the elements sodium and chlorine, represented in Figure 11.11. Notice that the sodium atoms (green) and the chlorine atoms (yellow) are arranged in a three-dimensional repeating pattern—a crystal. Each sodium atom is surrounded by six chlorine atoms, and each chlorine atom is surrounded by six sodium atoms. Interestingly, there are no separate sodium–chlorine groups that can be labeled molecules.[3]

---

[3] In a strict sense, common table salt *is* a mixture—often with small amounts of potassium iodide and sugar. The iodine in the potassium iodide has virtually eliminated a common affliction of earlier times, a swelling of the thyroid gland known as endemic goiter. Tiny amounts of sugar prevent oxidation of the salt, which otherwise would turn yellow.

Molecules

A **molecule** consists of two or more atoms that bond together by sharing electrons. (We say such atoms are *covalently bonded.*) A molecule may be as simple as the two-atom combination of oxygen, O_2, or the two-atom combination of nitrogen, N_2, which are the elements that comprise most of the air we breathe. Two atoms of hydrogen combine with a single atom of oxygen to form a water molecule, H_2O. Changing a molecule by one atom can make a big difference. Replacing the oxygen atom with a sulfur atom produces hydrogen sulfide, H_2S, a strong-smelling, toxic gas.

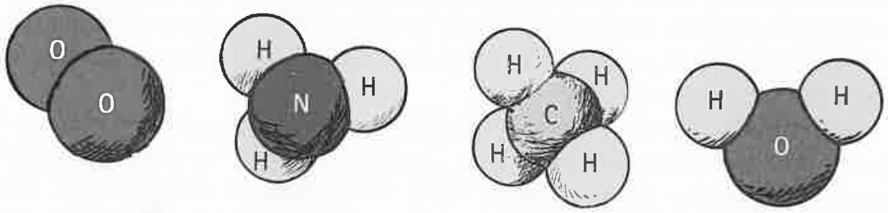


FIGURE 11.12

Models of simple molecules: O_2, NH_3, CH_4, and H_2O. The atoms in a molecule are not just mixed together, but are joined in a well-defined way.

CHECK POINT

How many atomic nuclei are in a single oxygen atom? In a single oxygen molecule?

Check Your Answer

There is one nucleus in an oxygen atom, O, and two in the combination of two oxygen atoms—an oxygen molecule, O_2.

Energy is required to pull molecules apart. We can understand this by considering a pair of magnets stuck together. Just as some "muscle energy" is required to pull the magnets apart, the breaking apart of molecules requires energy. During photosynthesis, plants use the energy of sunlight to break apart the bonds within atmospheric carbon dioxide and water to produce oxygen gas and carbohydrate molecules. These carbohydrate molecules retain this solar energy until the process is reversed—the plant is oxidized, either slowly by rotting or quickly by burning. Then the energy that came from the sunlight is released back into the environment. So the slow warmth of decaying compost or the quick warmth of a campfire is really the warmth of stored sunlight!

More things can burn besides those that contain carbon and hydrogen. Iron "burns" (oxidizes) too. That's what rusting is—the slow combination of oxygen atoms with iron atoms, releasing energy. When the rusting of iron is speeded up, it makes nice hand-warmer packs for skiers and winter hikers. Any process in which atoms rearrange to form different molecules is called a *chemical reaction.*

Our sense of smell is sensitive to exceedingly small quantities of molecules. Our olfactory organs easily detect small concentrations of such noxious gases as hydrogen sulfide (the stuff that smells like rotten eggs), ammonia, and ether. The smell of perfume is the result of molecules that rapidly evaporate and diffuse haphazardly in the air until some of them get close enough to your nose to be inhaled. They are just a few of the billions of jostling molecules that, in their aimless wanderings, happen to end up in the nose. You can get an idea of the speed of molecular diffusion in the air when you are in your bedroom and smell food very soon after the oven door has been opened in the kitchen.

Although H_2O is the major greenhouse gas in the atmosphere, CO_2, the second most abundant greenhouse gas, is notorious because its growth is attributable to human activity. Since further warming by CO_2 can trigger more H_2O, a present concern is the growing amounts of both gases in the atmosphere.

Antimatter

Whereas matter is composed of atoms with positively charged nuclei and negatively charged electrons, **antimatter** is composed of atoms with negative nuclei and positive electrons, or *positrons*.

Positrons were first discovered in 1932, in cosmic rays bombarding Earth's atmosphere. Today, antiparticles of all types are regularly produced in laboratories using large nuclear accelerators. A positron has the same mass as an electron and the same magnitude of charge, but the opposite sign. Antiprotons have the same mass as protons but are negatively charged. The first complete artificial anti-atom, a positron orbiting an antiproton, was constructed in 1995. Every charged particle has an antiparticle of the same mass and opposite charge. Neutral particles (such as the neutron) also have antiparticles, which are alike in mass and in some other properties but opposite in certain other properties. Every particle has an antiparticle. There are even antiquarks.

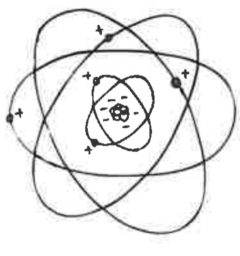


FIGURE 11.13
An atom of antimatter has a negatively charged nucleus surrounded by positrons.

Gravitational force does not distinguish between matter and antimatter—each attracts the other. Also, there is no way to indicate whether something is made of matter or antimatter by the light it emits. Only through much subtler, hard-to-measure nuclear effects could we determine whether a distant galaxy is made of matter or antimatter. But, if an antistar were to meet a star, it would be a different story. They would mutually annihilate each other, with most of the matter converting to radiant energy (this is what happened to the anti-atom created in 1995, when it encountered normal matter and rapidly annihilated in a puff of energy). This process, more so than any other known, results in the maximum energy output per gram of substance—$E = mc^2$, with a 100% mass conversion.[4] (Nuclear fission and fusion, by contrast, convert less than 1% of the matter involved.)

There cannot be both matter and antimatter in our immediate environment, at least not in appreciable amounts or for appreciable times. That's because something made of antimatter would be completely transformed to radiant energy as soon as it touched matter, consuming an equal amount of normal matter in the process. If the Moon were made of antimatter, for example, a flash of energetic radiation would result as soon as one of our spaceships touched it. Both the spaceship and an equal amount of the antimatter Moon would disappear in a burst of radiant energy. We know the Moon is not antimatter because this didn't happen during the Moon missions. (Actually, astronauts weren't in this kind of danger, for previous evidence showed that the Moon is made of ordinary matter.) But what about other galaxies? There is strong reason to believe that in the part of the universe we know (the "observable universe"), galaxies are made only of normal matter—apart from the occasional transitory antiparticle. But what of the universe beyond? Or other universes? We don't know.

"Science is a way to teach how something gets to be known, what is not known, to what extent things are known (for nothing is known absolutely), how to handle doubt and uncertainty, what the rules of evidence are, how to think about things so that judgments can be made, and how to distinguish truth from fraud and from show."— *Richard Feynman*

CHECK POINT

If a 1-gram body of antimatter meets a 10-gram body of matter, what mass survives?

Check Your Answer

Nine grams of matter survive (the other 2 grams are transformed into radiant energy).

---

[4] Some physicists speculate that right after the Big Bang, the early universe had billions of times more particles than it has now, and that a near total extinction of matter and antimatter caused by their mutual annihilation left only the relatively small amount of matter now present in the universe.

Dark Matter

We know that the elements in the periodic table are not confined to our planet. From studies of radiation coming from other parts of the universe, we find that stars and other objects "out there" are composed of the same particles we have on Earth. Stars emit light with the same "fingerprints" (*atomic spectra,* Chapter 30) as the elements in the periodic table. How wonderful to find that the laws that govern matter on Earth extend throughout the observable universe. Yet there remains one troubling detail. Gravitational forces within galaxies are measured to be far greater than visible matter can account for.

Finding the nature of the dark matter and the nature of the energy of empty space are high-priority quests in these times. What we will have learned by 2050 will likely dwarf all that we have ever known.

Astrophysicists talk of the **dark matter**—matter we can't see that tugs on stars and galaxies that we *can* see. In the closing years of the 20th century, astrophysicists confirmed that some 23% of matter in the universe is composed of the unseen dark matter. Whatever dark matter is, most or all of it is likely to be "exotic" matter—very different from the elements that make up the periodic table, and different from any extension of the present list of elements. Much of the rest of the universe is *dark energy,* which pushes outward on the expanding universe. Both dark matter and dark energy make up some 90% of the universe. Only in this 21st century has this type of energy been apparent. At this writing, neither has been identified. Speculations abound about dark matter and dark energy, but we don't know what they are.

Richard Feynman often used to shake his head and say he didn't know anything. When he and other top physicists say they don't know anything, they mean that what they *do* know is closer to nothing than to what they *can* know. Scientists know enough to realize that they have a relatively small handle on an enormous universe still full of mysteries. From a looking-backward point of view, today's scientists know enormously more than their forebears a century ago, and scientists then knew much more than *their* forebears. But, from our present vantage point, looking forward, there is so much yet to be learned. Physicist John A. Wheeler, Feynman's graduate-school advisor, envisioned the next level of physics going beyond *how* to *why*—to meaning. We have scarcely scratched the surface.

"I can live with doubt and uncertainty and not knowing. I think it is much more interesting to live not knowing than to have answers that might be wrong."—*Richard Feynman*

SUMMARY OF TERMS

Atom The smallest particle of an element that has all of the element's chemical properties.

Brownian motion The haphazard movement of tiny particles suspended in a gas or liquid resulting from their bombardment by the fast-moving atoms or molecules of the gas or liquid.

Electron Negatively charged particle that whizzes about within an atom.

Atomic nucleus The core of an atom, consisting of two basic subatomic particles—protons and neutrons.

Proton Positively charged particle in the nucleus of an atom.

Element A pure substance consisting of only one kind of atom.

Atomic number The number that designates the identity of an element, which is the number of protons in the nucleus of an atom; in a neutral atom, the atomic number is also the number of electrons in the atom.

Periodic table of the elements A chart that lists the elements in horizontal rows by their atomic number and in vertical columns by their similar electron arrangements and chemical properties. (See Figure 11.9.)

Ion An electrically charged atom; an atom with an excess or deficiency of electrons.

Isotope An atom of the same element that contains a different number of neutrons.

Atomic mass unit (amu) The standard unit of atomic mass, which is equal to 1/12 the mass of the most common atom of carbon. One amu has a mass of 1.661×10^{-27} kg.

Compound A material in which atoms of different elements are chemically bonded to one another.

Mixture A substance whose components are mixed together without combining chemically.

Molecule Two or more atoms that bond together by a sharing of electrons. Atoms combine to become molecules.

Antimatter A "complementary" form of matter composed of atoms with negative nuclei and positive electrons.

Dark matter Unseen and unidentified matter that is evident by its gravitational pull on stars in the galaxies. Dark matter, along with dark energy, constitutes perhaps 90% of the stuff of the universe.

REVIEW QUESTIONS

The Atomic Hypothesis

1. What causes dust particles and tiny grains of soot to move with Brownian motion?
2. Who first explained Brownian motion and made a convincing case for the existence of atoms?
3. According to Richard Feynman, when do atoms attract each other, and when do they repel?

Characteristics of Atoms

4. How does the approximate number of atoms in the air in your lungs compare with the number of breaths of air in Earth's atmosphere?
5. Are most of the atoms around us younger or older than the Sun?

Atomic Imagery

6. Why can atoms not be seen with a powerful optical microscope?
7. Why can atoms be seen with an electron beam?
8. What is the purpose of a model in science?

Atomic Structure

9. How does the mass of an atomic nucleus compare with the mass of an atom as a whole?
10. What is a nucleon?
11. How does the mass and electric charge of a proton compare with the mass and charge of an electron?
12. Since atoms are mostly empty space, why don't we fall through a floor we stand on?

The Elements

13. What element has the lightest atoms?
14. What is the most abundant element in the known universe?
15. How were elements heavier than hydrogen formed?
16. Where did the heaviest elements originate?
17. What are the five most common elements in living things?

The Periodic Table of the Elements

18. What does the atomic number of an element tell you about the element?
19. What is characteristic of the columns in the periodic table?

Relative Sizes of Atoms

20. What kind of basic force pulls electrons close to the atomic nucleus?
21. Why are heavier elements not much larger than lighter elements?

Isotopes

22. How does one isotope differ from another?
23. Distinguish between *mass number* and *atomic mass*.

Compounds and Mixtures

24. What is a compound? Cite three examples.
25. What is a mixture? Cite three examples.

Molecules

26. How does a molecule differ from an atom?
27. Compared with the energy it takes to separate oxygen and hydrogen from water, how much energy is released when they recombine? (In Chapter 5 you studied the conservation of energy.)

Antimatter

28. How do matter and antimatter differ?
29. What occurs when a particle of matter and a particle of antimatter meet?

Dark Matter

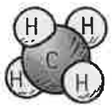
30. What is the evidence that dark matter exists?

RANKING

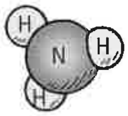
1. Consider the following atoms: A. Gold, B. Copper, C. Carbon, D. Silver.
   Consult the periodic table and rank these atoms, from most to least, by their
   a. mass.
   b. number of electrons.
   c. number of protons.
2. Rank the number of shells in these noble-gas atoms from most to least:
   a. Argon. b. Radon. c. Helium. d. Neon.
3. Rank the mass of these molecules from most to least.

A

B



C



D

PROJECTS

1. A candle will burn only if oxygen is present. Will a candle burn twice as long in an inverted liter jar as it will in an inverted half-liter jar? Try it and see.
2. Write a letter to Grandma or Grandpa and describe how long the atoms that make up their bodies have been around. And how long they will continue to be around.

EXERCISES

1. How many types of atoms can you expect to find in a pure sample of any element?
2. How many individual atoms are in a water molecule?
3. When a container of gas is heated, what happens to the average speed of its molecules?
4. The average speed of a perfume-vapor molecule at room temperature may be about 300 m/s, but you'll find the speed at which the scent travels across the room is much less. Why?
5. A cat strolls across your backyard. An hour later, a dog with his nose to the ground follows the trail of the cat. Explain this occurrence from a molecular point of view.
6. If no molecules in a body could escape, would the body have any odor?
7. Where were the atoms that make up a newborn infant "manufactured"?
8. Which of the following is not an element: hydrogen, carbon, oxygen, water?
9. Which of the following are pure elements: H_2, H_2O, He, Na, NaCI, H_2SO_4, U?
10. Your friend says that what makes one element distinct from another is the number of electrons about the atomic nucleus. Do you agree wholeheartedly, partially, or not at all? Explain.
11. What is the cause of the Brownian motion of dust particles? Why aren't larger objects, such as baseballs, similarly affected?
12. Why don't equal masses of golf balls and Ping-Pong balls contain the same number of balls?
13. Why don't equal masses of carbon atoms and oxygen atoms contain the same number of particles?
14. Which contains more atoms: 1 kg of lead or 1 kg of aluminum?
15. How many atoms are in a molecule of ethanol, C_2H_6O?
16. The atomic masses of two isotopes of cobalt are 59 and 60. (a) What is the number of protons and neutrons in each? (b) What is the number of orbiting electrons in each when the isotopes are electrically neutral?
17. A particular atom contains 29 electrons, 34 neutrons, and 29 protons. What is the identity of this element and its atomic number?
18. If two protons and two neutrons are removed from the nucleus of an oxygen atom, what nucleus remains?
19. What element results if you add a pair of protons to the nucleus of mercury? (See the periodic table.)
20. What element results if two protons and two neutrons are ejected from a radium nucleus?
21. To become a negative ion, does an atom lose or gain an electron?
22. To become a positive ion, does an atom lose or gain an electron?
23. You could swallow a capsule of germanium without ill effects. But, if a proton were added to each of the germanium nuclei, you would not want to swallow the capsule. Why? (Consult the periodic table.)
24. Helium is an inert gas, meaning that it doesn't readily combine with other elements. What five other elements would you also expect to be inert gases? (See the periodic table.)
25. Which of the following elements would you predict to have properties most like those of silicon (Si): aluminum (Al), phosphorus (P), or germanium (Ge)? (Consult the periodic table.)
26. A carbon atom, with a half-full outer shell of electrons—four in a shell that can hold eight—readily shares its electrons with other atoms and forms a vast number of molecules, many of which are the organic molecules that form the bulk of living matter. Looking at the periodic table, what other element do you think might play a role like carbon in life forms on some other planet?
27. Which contributes more to an atom's mass—electrons or protons? Which contributes more to an atom's size?
28. A hydrogen atom and a carbon atom move at the same speed. Which has the greater kinetic energy?
29. In a gaseous mixture of hydrogen and oxygen gas, both with the same average kinetic energy, which molecules move faster on average?
30. The atoms that constitute your body are mostly empty space, and structures such as the chair you're sitting on are composed of atoms that are also mostly empty space. So why don't you fall through the chair?
31. In what sense can you truthfully say that you are a part of every person in history? In what sense can you say that you will tangibly contribute to every person on Earth who will follow?
32. What are the chances that at least one of the atoms exhaled by your very first breath will be in your next breath?
33. Hydrogen and oxygen always react in a 1:8 ratio by mass to form water. Early investigators thought this meant that oxygen was 8 times more massive than hydrogen. What chemical formula did these investigators assume for water?
34. Somebody told your friend that if an antimatter alien ever set foot upon Earth, the whole world would explode into pure radiant energy. Your friend looks to you for verification or refutation of this claim. What do you say?
35. Make up a multiple-choice question that will test your classmates on the distinction between any two terms in the Summary of Terms list.

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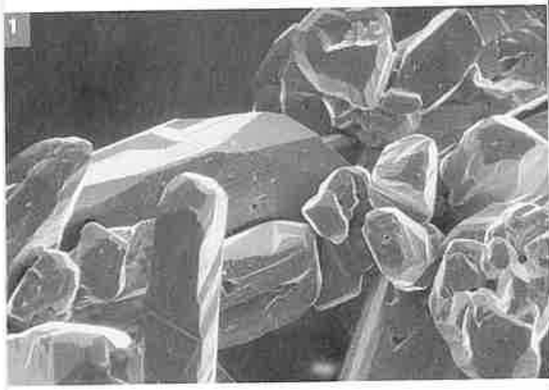
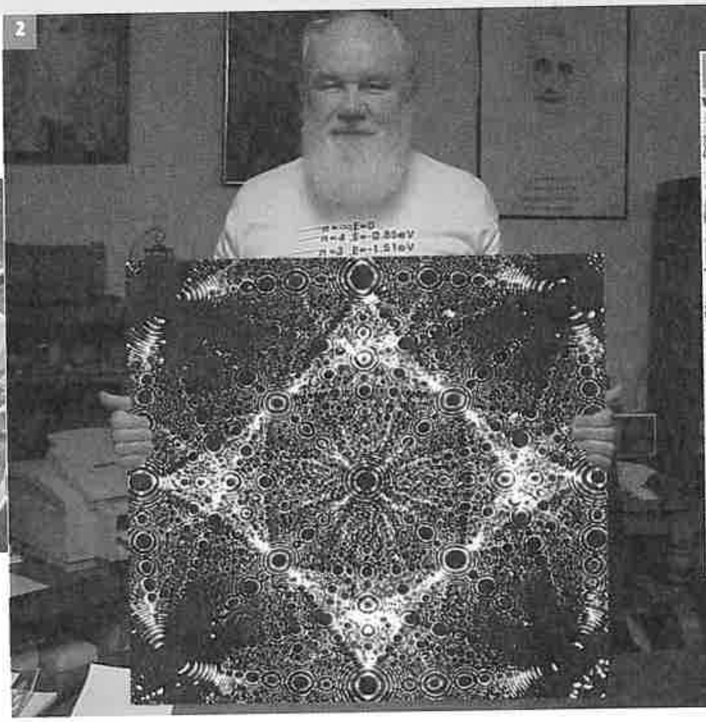




1 Silver crystals, close up. 2 John Hubisz displays an enlarged image of one of Eric Müller's famous micrographs. 3 Compression between adjacent stones accounts for the strength of semicircular arches, which for centuries have been used in the construction of doorways, bridges, and many structures.

Over two nights in February 1945, late in World War II, the German city of Dresden was firebombed, leveling the city and killing tens of thousands of its inhabitants. Beneath those bombs, and surviving, was the German physicist Erwin Wilhelm Müller.

Before the war, Müller invented the field emission microscope and later was the first person to experimentally observe atoms. After the war, in 1951, he invented the field ion microscope, which provided a sharper and clearer view of atoms in a crystal lattice. A sample of this is shown in the striking photograph above held by physicist John Hubisz. The photograph is a *micrograph,* produced in 1958 by Müller after he joined the faculty at Pennsylvania State University.

Müller used an extremely fine platinum needle with an incredibly tiny hemisphere-shaped tip. The needle was enclosed in a tube of rarefied helium and subjected to a very high positive voltage relative to its surroundings. This voltage created such an intense electric force that any helium atoms "settling" on the atoms of the needle tip were stripped of electrons to become *ions.* Positively charged helium ions streamed away from the platinum needle tip in a direction almost perpendicular to its surface at every point. They then struck a fluorescent screen, producing this picture of the needle tip, which magnifies the spacing of the atoms by approximately 750,000 times. Clearly, the platinum is crystalline, with the atoms arranged like oranges in a grocer's display. Although the photograph is not of the atoms themselves, it shows the positions of the atoms and reveals the microarchitecture of one of the solids that make up our world.

Crystal Structure

Metals, salts, and most minerals—the materials of Earth—are made up of crystals. People have known for centuries about crystals such as salt and quartz, but it wasn't until the 20th century that crystals were interpreted as regular arrays of atoms. In 1912, physicists used X-rays to confirm that each crystal is a three-dimensional orderly arrangement—a crystalline latticework of atoms. The atoms in a crystal were measured to be very close together, about the same distance apart as the wavelength of X-rays.

The German physicist Max von Laue discovered that a beam of X-rays directed upon a crystal is diffracted, or separated, into a characteristic pattern (Figure 12.1). X-ray *diffraction patterns* on photographic film show crystals to be neat mosaics of atoms sited on regular lattices, like three-dimensional chessboards or children's jungle gyms. Such metals as iron, copper, and gold have relatively simple crystal structures. Tin and cobalt are a little more complex. All metals contain a jumble of many crystals, each almost perfect, with the same regular lattice but at some inclination to the crystal nearby. These metal crystals can be seen when a metal surface is *etched,* or cleaned, with acid. You can see the crystal structures on the surface of galvanized iron exposed to the weather, or on brass doorknobs etched by the perspiration of many hands.

Von Laue's photographs of the X-ray diffraction patterns fascinated English scientists William Henry Bragg and his son William Lawrence Bragg. They developed a mathematical formula that showed just how X-rays should scatter from the various regularly spaced atomic layers in a crystal. With this formula and an analysis of the pattern of spots in a diffraction pattern, they could determine distances between the atoms in a crystal. X-ray diffraction is a vital tool today in the biological and physical sciences.

Noncrystalline solids are said to be *amorphous.* In the amorphous state, atoms and molecules in a solid are distributed randomly. Rubber, glass, and plastic are among the materials that lack an orderly, repetitive arrangement of their basic particles. In many amorphous solids, the particles have some freedom to wander. This is evident in the elasticity of rubber and the tendency of glass to flow when subjected to stress over long periods of time.

Whether atoms are in a crystalline state or in an amorphous state, each atom or ion vibrates about its own position. Atoms are tied together by electrical bonding forces. We'll not discuss **atomic bonding** now, except to mention the four principal types of bonding in solids: ionic, covalent, metallic, and Van der Waals', the last being the weakest. Some properties of a solid are determined by the types of bonds it has. More information about these bonds can be found in almost any chemistry text.

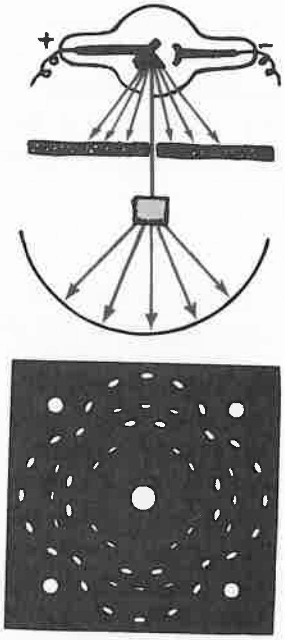


FIGURE 12.1

X-ray determination of crystal structure. The photograph of common table salt (sodium chloride) is a product of X-ray diffraction. Rays from the X-ray tube are blocked by a lead screen except for a narrow beam that hits the salt crystal. The radiation that penetrates the crystal and reaches the photographic film makes the pattern shown. The white spot in the center is due to the main unscattered beam of X-rays. The size and arrangement of the other spots result from the latticework structure of sodium and chlorine ions in the crystal. A crystal of sodium chloride always produces this same design. Every crystalline structure has its own unique X-ray diffraction picture.

fyi

- Humans have been using solid materials for many thousands of years. The names of the time periods Stone Age, Bronze Age, and Iron Age tell us the importance of solid materials in the development of civilization. The numbers and uses of materials multiplied over the centuries, yet there was little progress in understanding the nature of solids. This understanding had to await discoveries about atoms that occurred in the 20th century. With that knowledge, investigators now invent new materials daily, meeting the demands of today's information age.

Diffraction patterns of DNA (similar to the one of salt shown here), made by Maurice Wilkins and Rosalind Franklin in 1953, provided the data from which James D. Watson and Francis Crick discovered the double helix of DNA.

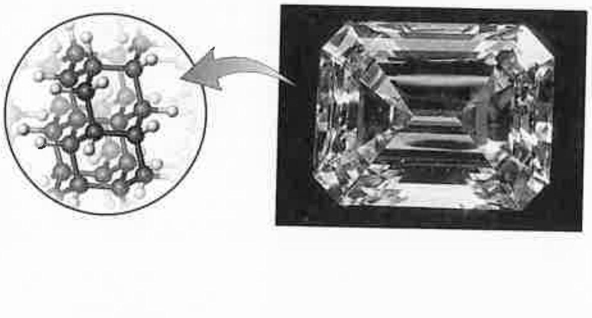


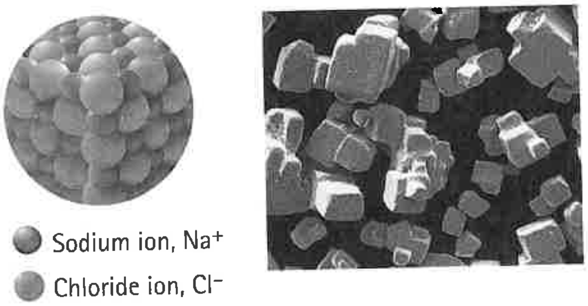
FIGURE 12.2

The crystalline structure of diamond is illustrated with sticks to represent the covalent bonds responsible for its extreme hardness.

The Van der Waals force is the mechanism that provides adhesion of the many ridges in the feet of a gecko.

FIGURE 12.3

The cubic crystalline structure of common salt as seen through a microscope. The cubic shape is a consequence of the cubic arrangement of sodium and chloride ions.



Density

Is iron heavier than wood? The question is ambiguous, for it depends on the amounts of iron and wood. A large log is clearly heavier than an iron nail. A better question to ask is if iron is *denser* than wood, in which case the answer is *yes,* iron is denser than wood. The masses of the atoms and the spacing between them determine the **density** of materials. We think of density as the "lightness" or "heaviness" of materials of the same size. It's a measure of the compactness of matter, of how much mass occupies a given space; it is the amount of mass per unit volume:

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

FIGURE 12.4

When the volume of the bread is reduced, its density increases.

Density is a property of a material; it doesn't matter how much of the material you actually have. The densities of a few materials are shown in Table 12.1. Density

Crystal Power

The regularly repeating internal structure of atoms in crystals gives them aesthetic properties that have long made them attractive in jewelry. Crystals also have properties that are very important to the electronics and optical industries, and they are used in just about every type of modern technology. In times past, crystals were valued for their alleged healing powers. This belief continues today, particularly among occultists and New Age healers. Crystals are said to channel "good energy" and ward off "bad energy." They carry "vibrations" that resonate with healing "frequencies" that help maintain a beneficial body balance. When properly arranged, crystals are said to provide protection against harmful electromagnetic forces emitted by power lines, cellular phones, computer monitors, microwave ovens, and other people. We are told that crystals are "medically proven" to heal and to protect and that such claims are "based on Nobel Prize–winning physics."

Crystals *do* give off energy—as every other object does. We'll learn in Chapter 16 that all things radiate energy—and also that all things absorb energy. If a crystal or any substance radiates more energy than it receives, its temperature drops. Atoms in crystals *do* vibrate and *do* resonate with matching frequencies of external vibrations—just as molecules in all gases and in all liquids do. If purveyors of crystal power are talking about some kind of energy special to crystals, or to life, no scientific evidence supports this (the discoverer of such a special kind of energy would quickly become world-famous). Of course, evidence for a new kind of energy, such as the dark energy discussed in the previous chapter, could one day be found, but this is not what is claimed by purveyors of crystal power, who assert that modern scientific evidence supports their claims.

The evidence for crystal power is not experimental; rather, it is confined to *testimonials.* As advertising illustrates, people are generally more persuaded by testimonials than by confirmed facts. Testimonials by people who are convinced of the personal benefits of crystals are common. Being convinced by scientific evidence is one thing; being convinced by wishful thinking, communal reinforcement, or by a placebo effect is quite another. None of the claims for the special powers of crystals have ever been backed up by scientific evidence.

Claims aside, wearing crystal pendants seems to give some people a good *feeling,* and even a feeling of protection. These feelings, and the aesthetic qualities of crystals, are their virtues. Some people feel that crystals bring good luck, just as carrying a rabbit's foot in your pocket is supposed to do. The difference between crystal power and rabbit's feet, however, is that the benefits of crystals are couched in scientific terms, whereas claims for the benefits of carrying a rabbit's foot are not. Hence, the purveyors of crystal power are into full-fledged pseudoscience.

is usually expressed with metric units, generally kilograms per cubic meter, kilograms per liter, or grams per cubic centimeter. Water, for example, has a mass density of 1000 kg/m^3, or, equivalently, 1 g/cm^3. So the mass of a cubic meter of fresh water is 1000 kg, and, equivalently, the mass of a cubic centimeter (about the size of a sugar cube) of fresh water is 1 g.

Density may be expressed in terms of weight rather than mass. This is *weight density,* which is defined as weight per unit volume:

$$\text{Weight density} = \frac{\text{weight}}{\text{volume}}$$

Weight density is measured in N/m^3. Because a 1-kg body has a weight of 9.8 N, weight density is numerically 9.8 × mass density. For example, the weight density of water is 9800 N/m^3. In the British system, 1 cubic foot (ft^3) of fresh water (almost 7.5 gallons) weighs 62.4 pounds. Thus, in the British system, fresh water has a weight density of 62.4 lb/ft^3.

The density of a material depends upon the masses of the individual atoms that make it up and the spacing between those atoms. Iridium, a hard, brittle, silvery-white metal in the platinum family, is the densest substance on Earth. Although the individual iridium atom is less massive than individual atoms of platinum, gold, lead, or uranium, the close spacing of iridium atoms in the crystalline form contributes to its greater density. More iridium atoms fit into a cubic centimeter than other, more massive but more widely spaced atoms. Hence iridium has a whopping density of 22,650 kg/m^3.

TABLE 12.1

Densities of Common Substances (kg/m^3) (for density in g/cm^3, divide by 1000)

Solids	Density
Iridium	22,650
Osmium	22,610
Platinum	21,090
Gold	19,300
Uranium	19,050
Lead	11,340
Silver	10,490
Copper	8,920
Brass	8,600
Iron	7,870
Tin	7,310
Aluminum	2,700
Concrete	2,300
Ice	919
Liquids	
Mercury	13,600
Glycerin	1,260
Seawater	1,025
Water at 4°C	1,000
Ethyl alcohol	785
Gasoline	680

CHECK POINT

1. *Here's an easy one:* When water freezes, it expands. What does this say about the density of ice compared with the density of water?
2. *Here's a slightly tricky one:* Which weighs more, a liter of ice or a liter of water?
3. Which has the greater density—100 kg of lead or 1000 kg of aluminum?
4. What is the density of 1000 kg of water?
5. What is the volume of 1000 kg of water?

Check Your Answers

1. Ice is less dense than water (because it has more volume for the same mass), which is why ice floats on water.
2. Don't say that they weigh the same! A liter of water weighs more. If it is frozen, then its volume will be more than a liter. If you shave that part off so that the chunk of ice is the same size as the original liter of water, it will certainly weigh less.
3. Density is a *ratio* of mass and volume (or weight and volume), and this ratio is greater for any amount of lead than for any amount of aluminum—see Table 12.1.
4. The density of *any* amount of water is 1000 kg/m^3 (or 1 g/cm^3).
5. The volume of 1000 kg of water is 1 m^3.

Elasticity

When an object is subjected to external forces, it undergoes changes in size, or in shape, or in both. The changes depend on the arrangement and bonding of the atoms in the material. A spring, for example, can be stretched or compressed by external forces.

A weight hanging on a spring stretches the spring. Additional weight stretches it further. If the weights are removed, the spring returns to its original length. We say

FIGURE 12.5

Both Stephanie and the tree are composed mainly of hydrogen, oxygen, and carbon. Food ingestion supplies these to Stephanie, whereas the tree gets most of its oxygen and carbon from the air. In this sense, a tree can be thought of as "solid air."

that the spring is *elastic.* When a batter hits a baseball, the bat temporarily changes the ball's shape. An archer, about to shoot an arrow, first bends the bow, which springs back to its original shape when the arrow is released. The spring, the baseball, and the bow are examples of elastic objects. A body's **elasticity** describes how much it changes shape when a deforming force acts upon it, and how well it returns to its original shape when the force is removed. Clay, putty, and dough do *not* return to their original shape when a deforming force is applied and then removed. Materials such as these, which do not resume their original shape after being deformed, are said to be *inelastic.* Lead is also inelastic, since it's easy to distort lead's shape permanently.

When you hang a weight on a spring, the weight applies a force to the spring and this stretches the spring. Twice the weight causes twice as much stretch; triple the force causes triple the stretch. We can say,

$$F \sim \Delta x$$

That is, the stretch is directly proportional to the applied force (Figure 12.7). This relationship, noted in the mid-17th century by the British physicist Robert Hooke, a contemporary of Isaac Newton, is called **Hooke's law.**

If an elastic material is stretched or compressed beyond a certain amount, it will not return to its original state and will remain distorted. The distance beyond which permanent distortion occurs is called the *elastic limit.* Hooke's law holds only as long as the force does not stretch or compress the material beyond its elastic limit.

A cubic meter is a sizable volume and contains a million cubic centimeters, so there are a million grams of water in a cubic meter (or, equivalently, a thousand kilograms of water in a cubic meter). Hence, 1 g/cm³ = 1000 kg/m³.

fyi

- The enamel in your teeth is the hardest substance in your body.

FIGURE 12.6

A baseball is elastic.

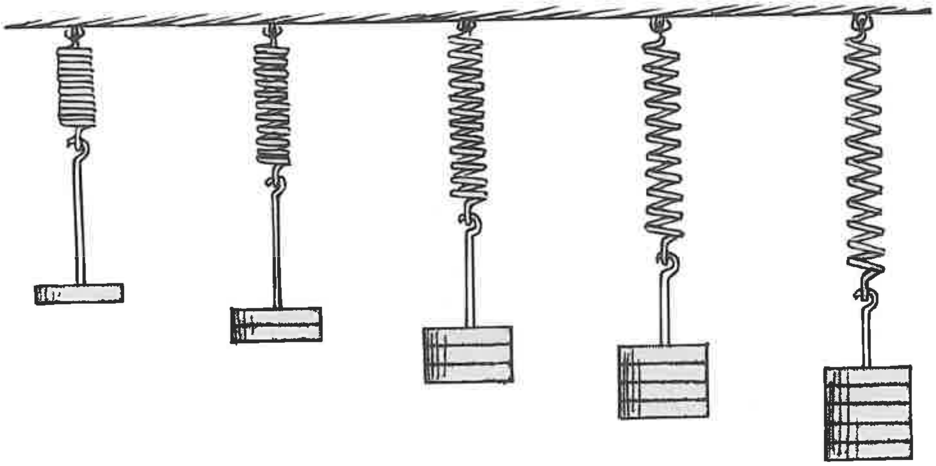


FIGURE 12.7

The stretch of the spring is directly proportional to the applied force. If the weight is doubled, the spring stretches twice as much.

fyi

- Robert Hooke, one of England's greatest scientists, was the first to propose a wave theory of light and the first to describe the cell (for which he became known as the father of microscopy). As an artist and surveyor, he helped Christopher Wren rebuild London after the great fire in 1766. As a physicist, he collaborated with Robert Boyle and other physicists of his time and was chosen to head the Royal Society. Upon Hooke's death, Isaac Newton became president of the Royal Society, and he jealously destroyed everything he could of Hooke's work. No paintings or likenesses of Robert Hooke survive today.

CHECK POINT

1. A 2-kg antique painting is hung from the end of a spring. The spring then stretches a distance of 10 cm. If, instead, a 4-kg painting is hung from the same spring, how much will the spring stretch? What if a 6-kg painting were hung from the same spring? (Assume that none of these loads stretches the spring beyond its elastic limit.)
2. If a force of 10 N stretches a certain spring 4 cm, how much stretch will occur for an applied force of 15 N?

Check Your Answers

1. A 4-kg load (painting in this case) has twice the weight of a 2-kg load. In accord with Hooke's law, $F \sim \Delta x$, 2 times the applied force results in 2 times the stretch, so the spring should stretch 20 cm. The weight of the 6-kg load makes the spring stretch 3 times as far, 30 cm. (If the elastic limit were exceeded, the amount of stretch could not be predicted with the information given.)

2. The spring will stretch 6 cm. By ratio and proportion, (10 N)/(4 cm) = (15 N)/(x cm), which is read: 10 newtons is to 4 centimeters as 15 newtons is to x centimeters; $x = 6$ cm. If taking a lab, you'll learn that the ratio of force to stretch is called the *spring constant*, k (in this case $k = 2.5$ N/cm), and Hooke's law is expressed as the equation $F = k\Delta x$.

Tension and Compression

When something is pulled on (stretched), it is said to be in *tension.* When it is pushed in (squashed), it is in *compression.* If you bend a ruler (or any stick), the part bent on the outside of the curve is in tension. The inner curved part, which is pushed in, is in compression. Compression causes things to get shorter and wider, whereas tension causes them to get longer and thinner. This is not obvious for most rigid materials, however, because the shortening or lengthening is very small.

Steel is an excellent elastic material, because it can withstand large forces and then return to its original size and shape. Because of its strength and elastic properties, it is used to make not only springs but construction girders as well. Vertical girders of steel used in the construction of tall buildings undergo only slight compression. A typical 25-meter-long vertical steel girder (column) used in high-rise construction is compressed about a millimeter when it carries a 10-ton load. This can add up. A 70- to 80-story building can compress the huge steel columns at its base by some 2.5 centimeters (a full inch) when construction is completed.

More deformation occurs when girders are used horizontally, where their tendency is to sag under heavy loads. When a horizontal beam is supported at one or both ends, it is under both tension and compression from its weight and the load it supports. Consider the horizontal beam supported at one end (known as a cantilever beam) in Figure 12.8. It sags because of its own weight and because of the load it supports at its end. A little thought will show that the top part of the beam tends to be stretched. Atoms tend to be pulled apart. The top part is slightly longer and is under tension. More thought shows that the bottom part of the beam is squashed. It is compressed as atoms there are squeezed together. The bottom part is slightly shorter because of the way it is bent. Can you see that, somewhere between the top and bottom, there is a region in which nothing happens, in which there is neither tension nor compression? This is the *neutral layer.*

A diving board with a diver standing at one end is a cantilever.

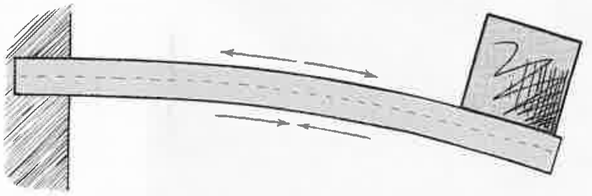


FIGURE 12.8

The top part of the beam is stretched and the bottom part is compressed. What happens in the middle portion, between top and bottom?

The horizontal beam shown in Figure 12.9, known as a simple beam, is supported at both ends and carries a load in the middle. Here there is compression in the top of the beam and tension in the bottom part. Again, there is a neutral layer along the middle portion of the thickness of the beam all along its length.

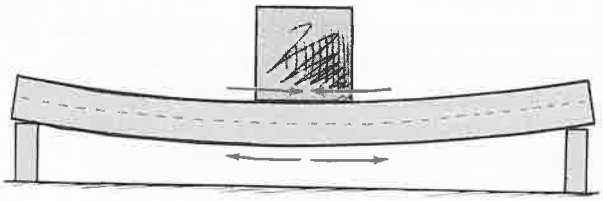
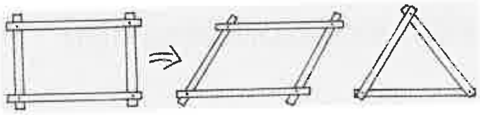


FIGURE 12.9

The top part of the beam is compressed and the bottom part is stretched. Where is the neutral layer (the part that is not under stress due to tension or compression)?

Practicing Physics

If you nail four sticks together to form a rectangle, they can be deformed into a parallelogram without too much effort. But, if three sticks are nailed together to form a triangle, the shape cannot be changed without actually breaking the sticks or dislodging the nails. The triangle is the strongest of all the geometrical figures, which is why you see triangular shapes in bridges. Go ahead and nail three sticks together and try this out, and then look at the triangles used in strengthening structures of many kinds.



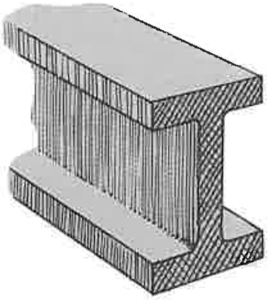


FIGURE 12.10

An I-beam is like a solid bar with some of the steel scooped from its middle where it is needed least. The beam is therefore lighter, but it has nearly the same strength.

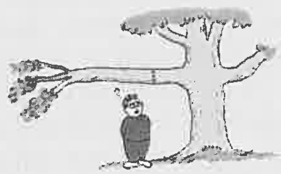
With the neutral layer in mind, we can see why the cross section of steel girders has the form of the letter I (Figure 12.10). Most of the material in these I-beams is concentrated in the top and bottom *flanges.* When the beam is used horizontally in construction, the stress is predominantly in the top and bottom flanges. One flange is squeezed while the other is stretched, the two flanges supporting virtually all stresses in the beam. Between the flanges is a relatively stress-free region, the *web,* that acts principally to hold the top and bottom flanges well apart. Because of the web, comparatively little material is needed. An I-beam is nearly as strong as a solid rectangular bar of the same overall dimensions, with considerably less weight. A large rectangular steel beam on a certain span might fail under its own weight, whereas an I-beam of the same depth could support much added load.

FIGURE 12.11

The upper half of each horizontal branch is under tension because of the branch's weight, while the lower half is under compression. In what location is the wood neither stretched nor compressed?

CHECK POINT

1. When you walk on floorboards in an old house that sag due to your weight, where is the neutral layer?
2. Suppose you drill a hole horizontally through a tree branch as shown. Where will the hole weaken the branch the least—through the upper portion, the middle portion, or the lower portion of the branch?



Check Your Answers

1. The neutral layer is midway between the top and bottom surfaces of the floorboards.
2. Drill the hole horizontally through the middle of the branch, through the neutral layer—a hole at that location will hardly affect the branch's strength because fibers there are neither stretched nor compressed. Wood fibers in the top part are being stretched, so a hole there may result in fibers pulling apart. Fibers in the lower part are compressed, so a hole there might crush under compression.

Arches

Stone breaks more easily under tension than compression. The roofs of stone structures built by the Egyptians during the time of the pyramids were constructed with many horizontal stone slabs. Because of the weakness of these slabs under the forces produced by gravity, many vertical columns had to be erected to support the roofs. Likewise for the temples in ancient Greece. Then came arches—and fewer vertical columns.

FIGURE 12.12

The horizontal slabs of stone of the roof cannot be too long because stone easily breaks under tension. That is why many vertical columns are needed to support the roof.

FIGURE 12.13

Common semicircular stone arches, which have stood for centuries.

Look at the tops of the windows in old brick buildings. Chances are the tops are arched. Likewise for the shapes of old stone bridges. When a load is placed on a properly arched structure, the compression strengthens rather than weakens the structure. The stones are pushed together more firmly and are held together by compressive forces. With just the right shape of the arch, the stones do not even need cement to hold them together.

When the load being supported is uniform and extends horizontally, as with a bridge, the proper shape is a parabola, the same curve followed by a thrown ball. The cables of a suspension bridge provide an example of an "upside-down" parabolic arch. If, on the other hand, the arch is supporting only its own weight, the curve that gives it maximum strength is called a *catenary.* A catenary is the curve formed by a rope or chain hung between two points of support. Tension along every part of the rope or chain is parallel to the curve. So, when a free-standing arch takes the shape of an inverted catenary, compression within it is everywhere parallel to the arch, just as tension between adjacent links of a hanging chain is everywhere parallel to the chain. The Gateway Arch, which graces the waterfront of St. Louis, Missouri, is a catenary (Figure 12.14).

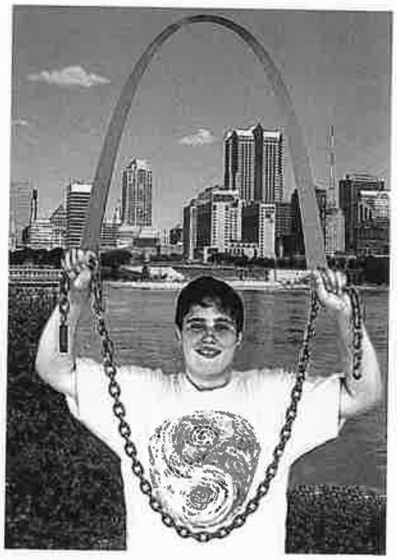


FIGURE 12.14

Both the curve of a sagging chain held by Manuel and the Gateway Arch in St. Louis are catenaries.

If you rotate an arch through a complete circle, you have a dome. The weight of the dome, like that of an arch, produces compression. Modern domes, such as the Astrodome in Houston, are inspired by three-dimensional catenaries, and they cover vast areas without the interruption of columns. There are shallow domes (the Jefferson Monument) and tall ones (the U.S. Capitol). And long before these, there were the igloos in the Arctic.

fyi

- A catenary arch could even be made with slippery blocks of ice! Provided that the compressive forces between blocks are parallel to the arch and that temperature doesn't rise enough to cause melting, the arch will remain stable.

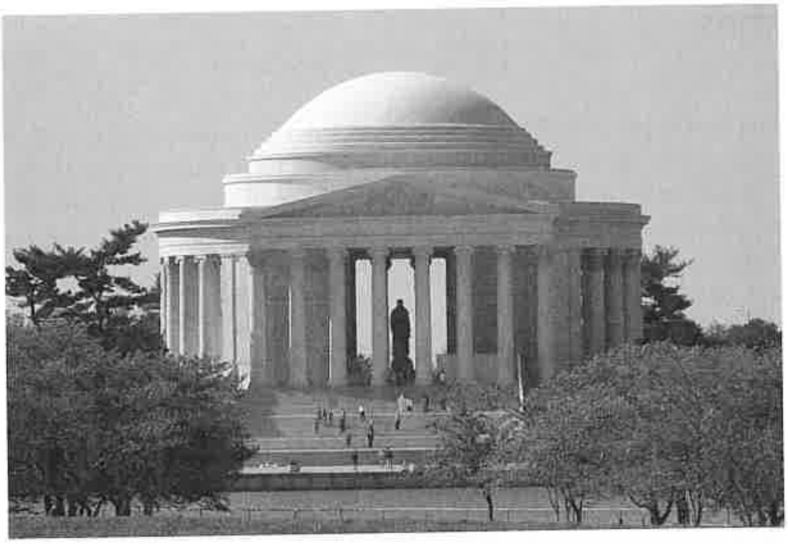


FIGURE 12.15

The weight of the dome produces compression, not tension, so no support columns are needed in the middle.

CHECK POINT

Why is it easier for a chicken inside an eggshell to poke its way out than it is for a chicken on the outside to poke its way in?

Check Your Answer

To poke its way into a shell, a chicken on the outside must contend with compression, which greatly resists shell breakage. But, when poking from the inside, only the weaker shell tension must be overcome. To see that the compression of the shell requires greater force, try crushing an egg along its long axis by squeezing it between your thumb and fingers. Surprised? Try it along its shorter diameter. Surprised? (Do this over a sink with some protection, such as gloves, for possible shell splinters.)

Scaling[1]

Have you ever noticed how strong an ant is for its size? An ant can carry the weight of several ants on its back, whereas a strong elephant would have great difficulty carrying even a single elephant. How strong would an ant be if it were scaled up to the size of an elephant? Would this "super ant" be several times stronger than an elephant? Surprisingly, the answer is *no.* Such an ant would be unable to lift its own weight off the ground. Its legs would be too thin for its greater weight, and they would likely break.

There is a reason for the thin legs of the ant and the thick legs of an elephant. As the size of a thing increases, it grows heavier much faster than it grows stronger. You can support a toothpick horizontally at its ends and notice no sag. But support an entire tree trunk of the same kind of wood horizontally at its ends and you'll notice an appreciable sag. Relative to its weight, the toothpick is much stronger than the tree. **Scaling** is the study of how the volume and shape (size) of any object affect the relationship of its strength, weight, and surface area.

Strength is related to the area of the cross section (which is two-dimensional and is measured in *square* centimeters), whereas *weight* relates to volume (which is three-

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Video
Scaling

Scaling was studied by Galileo, who differentiated the bone sizes of various creatures.

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[1] Material in this section is based on two delightful and informative essays: "On Being the Right Size," by J. B. S. Haldane, and "On Magnitude," by Sir D'Arcy Wentworth Thompson, both in James R. Newman (ed.), *The World of Mathematics,* vol. II. (New York: Simon & Schuster, 1956).

dimensional and is measured in *cubic* centimeters). To understand this square–cube relationship, consider the simplest case of a solid cube of matter, 1 centimeter on a side—say, a sugar cube. Any 1-cubic-centimeter cube has a cross section of 1 square centimeter. That is, if we sliced through the cube parallel to one of its faces, the sliced area would be 1 square centimeter. Compare this with a cube made of the same material that has double the linear dimensions—a cube 2 centimeters on each side. As shown in Figure 12.16, its cross-sectional area will be 2 × 2, or 4 square centimeters, and its volume will be 2 × 2 × 2, or 8 cubic centimeters. Therefore, the larger cube will be 4 times as strong but 8 times as heavy. Careful investigation of Figure 12.16 shows that, for increases of linear dimensions, the cross-sectional area and the total area grow as the square of the increase, whereas volume and weight grow as the cube of the increase.

A sphere has the least area per volume. Now you know why elevated water reservoirs are often spherical in shape.

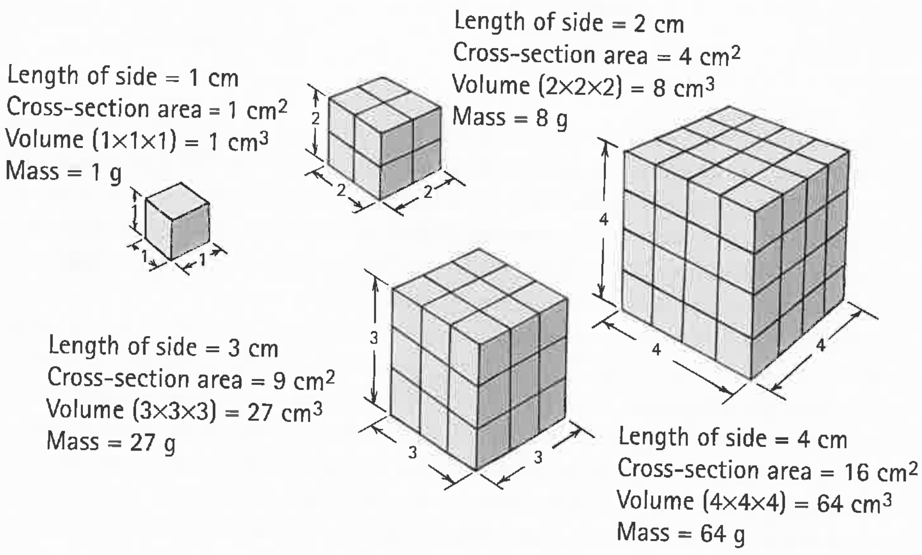

FIGURE 12.16

INTERACTIVE FIGURE

As the linear dimensions of an object change by some factor, the cross-sectional area changes as the square of this factor, and the volume (and hence the weight) changes as the cube of this factor. We see that, when the linear dimensions are doubled (factor 2), the area grows by $2^2 = 4$, and the volume grows by $2^3 = 8$.

Volume (and thus weight) increases much faster than the corresponding increase of cross-sectional area. Although Figure 12.16 demonstrates the simple example of a cube, the principle applies to an object of any shape. Consider a football player who can do many pushups. Suppose he could somehow be scaled up to twice his size—that is, twice as tall and twice as broad, with his bones twice as thick and every linear dimension increased by a factor of 2. Would he be twice as strong and be able to lift himself with twice the ease? The answer is *no.* Although his twice-as-thick arms would have four times the cross-sectional area and be four times as strong, he would be eight times as heavy. For comparable effort, he would be able to lift only half his weight. Relative to his new weight, he would be weaker than before.

We find in nature that large animals have disproportionately thick legs compared with those of small animals. This is because of the relationship between volume and area—the fact that volume (and weight) grows as the cube of the factor by which the linear dimension increases, while strength (and area) grows as the square of the increase factor. So we see that there is a reason for the thin legs of a deer or an antelope, as well as for the thick legs of a rhinoceros, a hippopotamus, or an elephant. So the great strengths attributed to King Kong and other fictional giants cannot be taken seriously. The fact that the consequences of scaling are conveniently omitted is one of the differences between science and science fiction.

Important also is the comparison of total surface area to volume (Figure 12.17). Total surface area, just like cross-sectional area, grows in proportion to the square of

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Video

Surface Area vs. Volume

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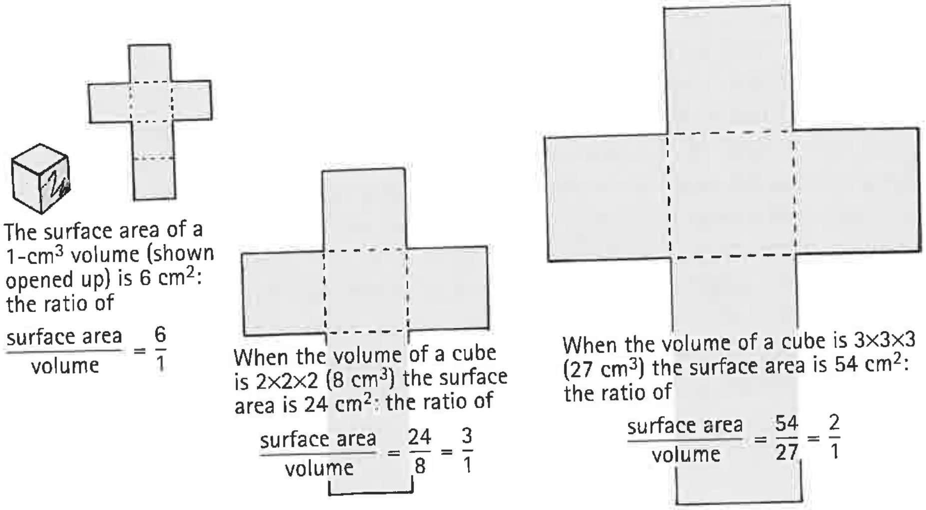
- Leonardo da Vinci was the first to report that the cross-sectional area of a tree trunk is equal to the combined surface areas produced by making a horizontal slice through all of the branches farther up on the tree (but perpendicular to each branch). Likewise for the cross-sectional areas of capillaries with the cross section of the vein that supplies blood to them.



The surface area of a 1-cm^3 volume (shown opened up) is 6 cm^2: the ratio of

$$\frac{\text{surface area}}{\text{volume}} = \frac{6}{1}$$

When the volume of a cube is 2×2×2 (8 cm^3) the surface area is 24 cm^2: the ratio of

$$\frac{\text{surface area}}{\text{volume}} = \frac{24}{8} = \frac{3}{1}$$

When the volume of a cube is 3×3×3 (27 cm^3) the surface area is 54 cm^2: the ratio of

$$\frac{\text{surface area}}{\text{volume}} = \frac{54}{27} = \frac{2}{1}$$

FIGURE 12.17

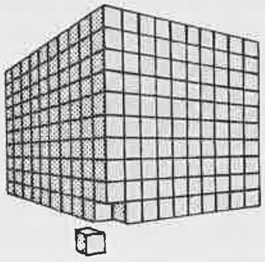
As the size of an object increases, there is a greater increase in its volume than in its surface area; as a result, the ratio of surface area to volume decreases.

an object's linear size, whereas volume grows in proportion to the cube of the linear size. So, as an object grows, its surface area and volume grow at different rates, with the result that the ratio of surface area to volume *decreases.* In other words, both the surface area and the volume of a growing object increase, but the growth of surface area *relative to* the growth of volume decreases. Not many people really understand this concept. The following examples may be helpful.

A chef knows that more potato peelings result from peeling 5 kg of small potatoes than from peeling 5 kg of large potatoes. Smaller objects have more surface area per kilogram. Thin french fries cook faster in oil than thicker french fries. Flattened hamburgers cook faster than meatballs of the same mass. Crushed ice will cool a drink much faster than a single ice cube of the same mass, because crushed ice presents more surface area to the beverage. Steel wool rusts away at the sink while steel knives rust more slowly. Iron rusts when exposed to air, but it rusts much faster, and is soon eaten away, if it is in the form of small strands or filings.

Burning is an interaction between oxygen molecules in the air and molecules on the surface of the fuel. That's why chunks of coal burn, while coal dust explodes when ignited, and why we light fires with several thin pieces of wood instead of the same mass of wood as a single log. These are all consequences of the fact that volume and area are not in direct proportion to each other.

CHECK POINT



1. Consider a 1-cm^3 cube scaled up to a cube 10 cm long on each edge.
   a. What would be the volume of the scaled-up cube?
   b. What would be its cross-sectional surface area?
   c. What would be its total surface area?
2. If you were somehow scaled up to twice your size while retaining your present proportions, would you be stronger or weaker? Explain your reasoning.

Check Your Answers

1. a. The volume of the scaled-up cube would be (length of side)^3 = (10 cm)^3, or 1000 cm^3.
   b. Its cross-sectional surface area would be (length of side)^2 = (10 cm)^2, or 100 cm^2.
   c. Its total surface area = 6 sides × area of a side = 6 × (10 cm)^2 = 600 cm^2.

2. Your scaled-up self would be four times as strong, because the cross-sectional area of your twice-as-thick bones and muscles increase by four. You could lift a load four times as heavy. But your weight would be eight times greater than before, so you would not be stronger relative to your greater weight. You have four times the strength but carry eight times the weight, which gives you a strength-to-weight ratio of only half its former value. So, if you can barely lift your own weight now, when scaled up you could lift only half your new weight. Your strength would increase, but your strength-to-weight ratio would decrease. Stay as you are!

FIGURE 12.18

The African elephant has less surface area relative to its weight than many other animals. It compensates for this with its large ears, which significantly increase its radiating surface area and promote cooling of the body.

The large ears of African elephants are nature's way of compensating for the small ratio of surface area to volume for these large creatures. The large ears may enhance hearing, but better, they enhance cooling. The rate at which a creature generates heat is proportional to its mass (or volume), but the heat that it can dissipate is proportional to its surface area. If an African elephant didn't have large ears, it would not have enough surface area to cool its huge mass. The large ears greatly increase its overall surface area, which facilitates cooling in hot climates.

At the microscopic level, living cells must contend with the fact that the growth of volume is faster than the growth of surface area. Cells obtain nourishment by diffusion through their surfaces. As cells grow, their surface area increases, but not fast enough to keep up with their increasing volume. For example, if the surface area increases by four, the corresponding volume increases by eight. Eight times as much mass must be sustained by only four times as much nourishment. At some size, the surface area isn't large enough to allow sufficient nutrients to pass into the cell, placing a limit on how large cells can grow. So cells divide, and there is life as we know it. That's nice.

FIGURE 12.19

The long tail of the monkey not only helps the monkey to maintain its balance but also effectively radiates excess heat.

Not so nice is the fate of large animals when they fall. The saying "The bigger they are, the harder they fall" holds true and is a consequence of the small ratio of surface area to weight. Air resistance to movement through the air depends on the surface area of the moving object. If you fell off a cliff, even with air resistance, your speed would increase at the rate of very nearly 1 *g*. Your terminal speed (the speed at which the force of air resistance on you equals your weight) would be large unless you wore a parachute to increase your surface area. Small animals need no parachute.

Scaling works for shrinking things too. If your linear dimensions got smaller by a factor of 10, your area would decrease by a factor of 100, but your weight would decrease by 1000. Being this small means that you'd have 10 times as much surface area relative to your weight, so you would have a much lower terminal speed. This is why an insect can fall from the top of a tree to the ground below without harm. The ratio of surface area per weight is in the insect's favor—in a sense, the insect is its own parachute.

The dissimilar consequences of a fall are just one illustration of the different relationships that large organisms and small organisms have with the physical environment. The force of gravity is tiny for insects compared with cohesion forces (stickiness) between their feet and the surfaces they walk on. That's why a fly can crawl up a wall or along the ceiling completely ignoring gravity. Humans and elephants can't do that. The lives of small creatures are ruled not by gravity but by such forces as surface tension, cohesion, and capillarity, which we'll treat in the next chapter.

It is interesting to note that the heartbeat rate of a mammal is related to the size of the mammal. The heart of a tiny shrew beats about 20 times faster than the heart of an elephant. In general, small mammals live fast and die young; larger animals live at a leisurely pace and live longer. Don't feel bad about a pet hamster that doesn't live as long as a dog. All warm-blooded animals have about the same life span—not in terms of years, but in the average number of heartbeats (about 800 million). Humans are the exception: we live two to three times longer than other mammals of our size.

Large raindrops fall faster than small raindrops, and large fish swim faster than small fish.

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- Raindrops can get as large as 8 mm in diameter. Drops about 1 mm in diameter are spherical; at 2 mm, they flatten like a hamburger bun; and at 5 mm, air resistance distorts them to parachute shapes. When circulation tosses raindrops back up into the air, often repeatedly, they may freeze and form hail. Hailstones have been recorded that are as large as 178 mm in diameter.

Researchers are finding that, when something shrinks enough—whether it's an electronic circuit, a motor, a film of lubricant, or an individual metal or ceramic crystal—it stops acting like a miniature version of its larger self and starts behaving in new and different ways. Palladium metal, for example, which is normally composed of grains about 1000 nanometers in size, is found to be five times as strong when formed from 5-nanometer grains.[2] Scaling is enormously important as more devices are being miniaturized.

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[2] A nanometer is one-billionth of a meter, so 1000 nanometers is one-millionth of a meter, or one-thousandth of a millimeter. Small indeed!

SUMMARY OF TERMS

Atomic bonding The linking together of atoms to form larger structures, including solids.

Density The mass of a substance per unit volume:

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

Weight density is weight per unit volume:

$$\text{Weight density} = \frac{\text{weight}}{\text{volume}}$$

Elasticity The property of a material wherein it changes shape when a deforming force acts upon it and returns to its original shape when the force is removed.

Hooke's law The amount of stretch or compression of an elastic material is directly proportional to the applied force:

$$F \sim \Delta x$$

When the spring constant k is introduced, $F = k\Delta x$.

Scaling The study of how size affects the relationships among weight, strength, and surface.

SUMMARY OF EQUATIONS

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

$$\text{Weight density} = \frac{\text{weight}}{\text{volume}}$$

$$F \sim \Delta x$$

REVIEW QUESTIONS

Crystal Structure

1. How does the arrangement of atoms in a crystalline substance differ from that in a noncrystalline substance?
2. What evidence can you cite for the microscopic crystal nature of certain solids? For macroscopic crystal nature?

Density

3. What happens to the volume of a loaf of bread that is squeezed? The mass? The density?
4. Which is denser, something having a density of 1000 kg/m^3 or something having a density of 1 g/cm^3? Defend your answer.
5. Iridium is not the heaviest atom found in nature. What, then, accounts for a chunk of pure iridium being the densest *substance* on Earth?
6. How does mass density differ from weight density?

Elasticity

7. Why do we say that a spring is elastic?
8. Why do we say a blob of putty is inelastic?
9. What is Hooke's law? Does it apply to elastic materials or to inelastic materials?
10. What is meant by the elastic limit for a particular object?
11. If a 1-kg object stretches a spring by 2 cm, how much will the spring be stretched when it supports a 3-kg object? (Assume the spring does not reach its elastic limit.)

Tension and Compression

12. Distinguish between *tension* and *compression.*
13. What and where is the neutral layer in a beam that supports a load?
14. Why are the cross sections of metal beams in the shape of the letter I instead of solid rectangles?

Arches

15. Why were so many vertical columns needed to support the roofs of stone buildings in ancient Egypt and Greece?
16. Is it *tension* or *compression* that strengthens an arch that supports a load?
17. Why is cement not needed between the stone blocks of an arch that has the shape of an inverted catenary?

18. Why are vertical columns not needed to support the middle of domed stadiums, such as the Houston Astrodome?

Scaling

19. Does the strength of a person's arm usually depend on the length of the arm or on its cross-sectional area?
20. What is the volume of a sugar cube that measures 1 cm on each side? What is the cross-sectional area of the cube? The total surface area?
21. If the linear dimensions of an object are doubled, by how much does the surface area increase? By how much does the volume increase?
22. As the volume of an object is increased, its surface area also increases. During this increase, does the *ratio* of square meters to cubic meters increase or does it decrease?
23. Which has more skin, an elephant or a mouse? Which has more skin *per unit of body weight,* an elephant or a mouse?
24. Why can small creatures fall considerable distances without injury, while people need parachutes to do the same?

RANKING

1. Consult Table 12.1 and rank the density of the following materials from greatest to least:
   a. concrete,
   b. liquid water,
   c. ice,
   d. aluminum.
2. Consider these three animals: A. dog, B. horse, C. elephant. Rank them, from highest to lowest, for their
   a. surface areas.
   b. masses.
   c. weights.
   d. volumes.
   e. surface area per weight.

PROJECTS

1. If you live in a region where snow falls, collect some snowflakes on black cloth and examine them with a magnifying glass. You'll see many hexagonal crystalline structures, among the most beautiful sights in nature.
2. Simulate atomic close packing with a couple of dozen or so pennies. Arrange them in a square pattern so each penny inside the perimeter makes contact with four others. Then arrange them hexagonally, so contact with six others occurs. Compare the areas occupied by the same number of pennies close packed both ways.
3. Are you slightly longer while lying down than you are tall when standing up? Make measurements and see.
4. Hold an egg vertically and dangle a small chain beside it. Can you see that the chain follows the contour of the egg—shallow sag for the more rounded end, and deeper sag for the more pointed end? Nature has not overlooked the catenary!

EXERCISES

1. You take 1000 mg of a vitamin and your friend takes 1 g of the same vitamin. Who takes more vitamins?
2. Your friend says that the primary difference between a solid and a liquid is the kind of atoms in the material. Do you agree or disagree, and why?
3. In what sense can it be said that a tree is solidified air?
4. Silicon is the chief ingredient of both glass and semiconductor devices, yet the physical properties of glass are different from those of semiconductor devices. Explain.
5. What evidence can you cite to support the claim that crystals are composed of atoms that are arranged in specific patterns?
6. What happens to the density of air in a common rubber balloon when it is heated?
7. Is iron necessarily heavier than cork? Explain.
8. How does the density of a 100-kg iron block compare with the density of an iron filing?
9. What happens to the density of water when it freezes to become ice?
10. In a deep dive, a whale is appreciably compressed by the pressure of the surrounding water. What happens to the whale's density during the dive?
11. The uranium atom is the heaviest and most massive atom among the naturally occurring elements. Why, then, isn't a solid bar of uranium the densest metal?
12. Which has more volume, a kilogram of gold or a kilogram of aluminum?
13. Which has more mass, a liter of ice or a liter of water?
14. How would you test the notion that a steel ball is elastic?
15. Why does the suspended spring stretch more at the top than at the bottom?

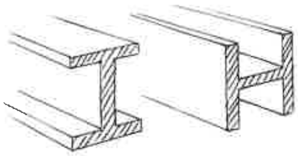
16. If the spring in the sketch above were supporting a heavy weight, how would the sketch be changed?
17. A thick rope is stronger than a thin rope of the same material. Is a long rope stronger than a short rope?

18. When you bend a meterstick, one side is under tension and the other is under compression. Which side is which?

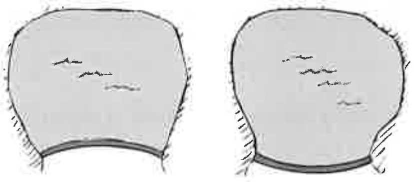
19. Tension and compression occur in a partially supported horizontal beam when it sags due to gravity or when it supports a load. Make a simple sketch to show a means of supporting the beam so that tension occurs at the top part and compression at the bottom. Sketch another case in which compression is at the top and tension occurs at the bottom.

20. Suppose you're constructing a balcony that extends beyond the main frame of your house. In a concrete overhanging slab, should steel reinforcing rods be embedded in the top, middle, or bottom of the slab?

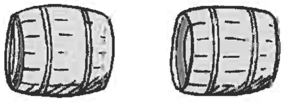
21. Can a horizontal I-beam support a greater load when the web is horizontal or when the web is vertical? Explain.



22. The sketches are of top views of a dam to hold back a lake. Which of the two designs is preferable? Why?



23. Consider a very large wooden barrel for storing wine. Should the "flat" ends be concave (bending inward) or convex (bending outward)? Why?



24. Why do you suppose that girders are so often arranged to form triangles in the construction of bridges and other structures? (Compare the stability of three sticks nailed together to form a triangle with four sticks nailed to form a rectangle, or any number of sticks to form multilegged geometric figures. Try it and see!)

25. Consider two bridges that are exact replicas of each other except that every dimension of the larger bridge is exactly twice that of the other—that is, twice as long, structural elements twice as thick, etc. Which bridge is more likely to collapse under its own weight?

26. Only with great difficulty can you crush an egg when squeezing it along its long axis, but it breaks easily if you squeeze it sideways. Why?

27. Archie designs an arch of a certain width and height to serve as an outdoor sculpture in a park. To achieve the size and shape for the strongest possible arch, he suspends a chain from two equally elevated supports as far apart as the arch is wide and allows the chain to hang as low as the arch is high. He then designs the arch to have exactly the inverted shape of the hanging chain. Explain why.

28. The photo shows a semicircular arch of stone. Note that it must be held together with steel rods to prevent outward movement. If the shape of the arch were not a semicircle but the shape used by Archie in the previous exercise, would the steel rods be necessary? Explain.

29. A candymaker making taffy apples decides to use 100 kg of large apples rather than 100 kg of small apples. Will the candymaker need to make more or less taffy to cover the apples?

30. Why is it easier to start a fire with kindling rather than with large sticks and logs of the same kind of wood?

31. Why does a chunk of coal burn when ignited, whereas coal dust explodes?

32. Why does a two-story house that is roughly a cube suffer less heat loss than a rambling one-story house of the same volume?

33. Why is heating more efficient in large apartment buildings than in single-family dwellings?

34. Some environmentally conscious people build their homes in the shape of a dome. Why is less heat lost in a dome-shaped dwelling than in a conventional dwelling with the same volume?

35. Why does crushed ice melt faster than the same mass of ice cubes?

36. Why do some animals curl up into a ball when they are cold?

37. Why is rust a greater problem for thin iron rods than for thick iron piles?

38. Why do thin french fries cook faster than thick fries?

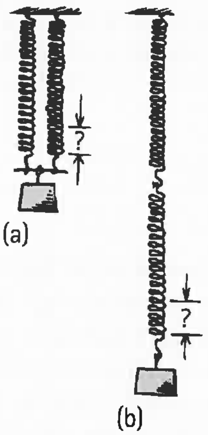
39. If you are grilling hamburgers and getting impatient, why is it a good idea to flatten the burgers to make them wider and thinner?

40. If you use a batch of cake batter for cupcakes and bake them for the time suggested for baking a cake, what will be the result?

41. Why are mittens warmer than gloves on a cold day? And which parts of the body are most susceptible to frostbite? Why?
42. What is the advantage to a gymnast of being short in stature?
43. How does scaling relate to the fact that the heartbeat of large creatures is generally slower than the heartbeat of smaller creatures?
44. Nourishment is obtained from food through the inner surface area of the intestines. Why is it that a small organism, such as a worm, has a simple and relatively straight intestinal tract, while a large organism, such as a human being, has a complex and extensively folded intestinal tract?
45. The human lungs have a volume of only about 4 L, yet an internal surface area of nearly 100 m^2. Why is this important, and how is this possible?
46. What does the concept of scaling have to do with the fact that living cells in a whale are about the same size as those in a mouse?
47. Which fall faster, large or small raindrops?
48. Who has more need for drink in a dry desert climate, a child or an adult?
49. Why doesn't a hummingbird soar like an eagle and an eagle flap its wings like a hummingbird?
50. Can you relate the idea of scaling to the governance of small versus large groups of citizens? Explain.

PROBLEMS

1. Show that the density of a 5-kg solid cylinder that is 10 cm tall with a radius of 3 cm is 17.7 g/cm^3.
2. What is the weight of a cubic meter of cork? Could you lift it? (For the density of cork, use 400 kg/m^3.)
3. A certain spring stretches 6 cm when a load of 30 N is suspended from it. How much will the spring stretch if 50 N is suspended from it (and it doesn't reach its elastic limit)?
4. Consider a spring that stretches 4 cm when a load of 10 N is suspended from it. How much will the spring stretch if an identical spring also supports the load as shown in (a) and (b)? (Neglect the weights of the springs.)



5. A cube 2 cm on a side is cut into cubes 1 cm on a side.
   a. How many cubes result?
   b. What was the surface area of the original cube and what is the total surface area of the eight smaller cubes? What is the ratio of surface areas?
   c. Show that the surface-to-volume ratio of the smaller cube is twice as great as for the single larger cube.
6. A 19.3-g mass of gold in the form of a cube is 1 cm long on each side (somewhat smaller than a sugar cube). What would be the length of the sides of a cube having twice this mass of gold?
7. In 2009, one of the U.S government's bailout packages was $700 billion when gold was worth $800 per ounce ($28.20 per gram). Calculate the mass in grams of $700 billion worth of gold. If this amount of gold were in the shape of a cube, how long would each of its sides be?

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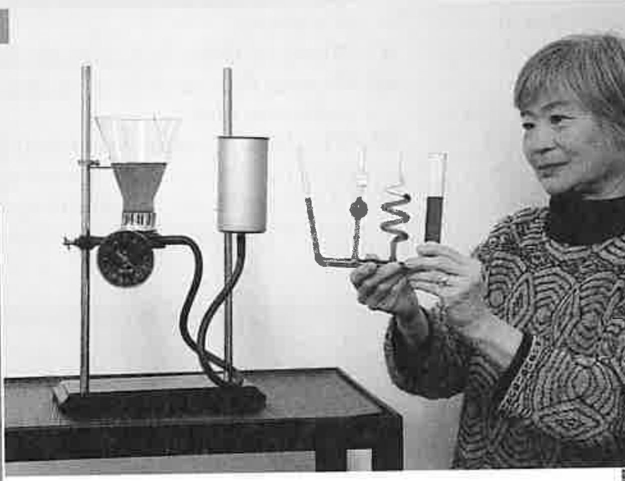
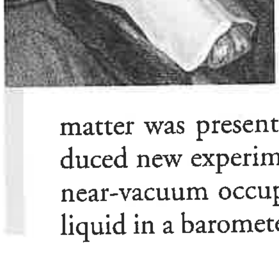


1 The depth of water above ground level in the tower ensures substantial and reliable water pressure to the many homes it serves. 2 When Tsing Bardin shows her class Pascal's vases, she asks how the same levels of colored water relate to the saying that "water seeks its own level." 3 The Falkirk Wheel in Scotland lifts boats 18 m from a lower body of water to a higher one with ease. While one water-filled caisson rotates upward, the other rotates downward, always balanced regardless of the weights of boats it may or may not carry.



Blaise Pascal was an outstanding 17th-century scientist, writer, and theologian. In investigating the physics of fluids he invented the hydraulic press that uses hydraulic pressure to multiply force. He also invented the syringe. Pascal's notoriety was prompted by his commentary on Evangelista Torricelli's experimentation with barometers. Pascal questioned what force kept some mercury in the tube and what filled the space above the mercury in the tube. Most scientists at the time, in the spirit of Aristotle, didn't believe a vacuum was possible and thought some invisible matter was present in the "empty space." Pascal produced new experiments and contended that, indeed, a near-vacuum occupies the space above the column of liquid in a barometer tube.

Pascal, in poor health all his life, enlisted his brother-in-law to carry a barometer up the slope of a high mountain to investigate the effect on the mercury level in the tube. As Pascal hypothesized, the level of mercury dropped with increased altitude. Pascal conducted a more modest version of the experiment by carrying a barometer up to the top of a church bell tower, a height of about 50 meters. Again the mercury level dropped, but not as much. These, and other experiments of Pascal, were hailed throughout Europe as establishing the principle and value of the barometer.

To answer the criticism that some invisible matter must exist in the empty space, Pascal called on the scientific method and replied: "In order to show that a hypothesis is evident, it does not suffice that all the phenomena follow from it; instead, if it leads to something contrary to a single one of the phenomena, that suffices to establish its falsity." His insistence on the existence of the vacuum also led to conflict with other prominent scientists, including Descartes.

Pascal's work with hydraulics led him to what is now called Pascal's Principle: "A change in pressure at any point in an enclosed fluid at rest is transmitted undiminished to all points in the fluid." Ropes and pulleys have given way to this principle, as hydraulic devices multiply forces unimagined before the time of Pascal.

Although a devout theologian, Pascal took issue with some of the dogmas of the time. Some of his writings on religion were banned by the Church. As a scientist, he is remembered for the hydraulics that subsequently changed the technological landscape; as a theologian, he is remembered for his many assertions, one of which relates to centuries of human landscape: "Men never do evil so cheerfully and completely as when they do so from religious convictions."

Today, in honor of his scientific contributions, the name Pascal has been given to the SI unit of pressure and to a computer programming language. In literature, Pascal is regarded as one of the most important authors of the mid-17th century. His use of satire and wit influenced writers around the world.

Pressure

A liquid contained in a vessel exerts forces against the walls of the vessel. To discuss the interaction between the liquid and the walls, it is convenient to introduce the concept of **pressure.** Pressure is a force divided by the area over which the force is exerted.[1]

$$\text{Pressure} = \frac{\text{force}}{\text{area}}$$

As an illustration of the distinction between pressure and force, consider the two blocks in Figure 13.1. The blocks are identical, but one stands on its end and the other rests on its side. Both blocks are of equal weight and therefore exert the same force on the surface (if you were to put them on a bathroom scale, each would register the same), but the upright block exerts a greater *pressure* against the surface. If the block were tipped up so that its contact with the table were on a single corner, the pressure would be greater still.

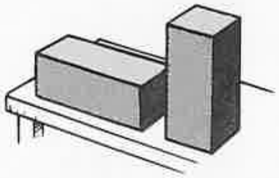


FIGURE 13.1

Although the weight of both blocks is the same, the upright block exerts greater pressure against the table.

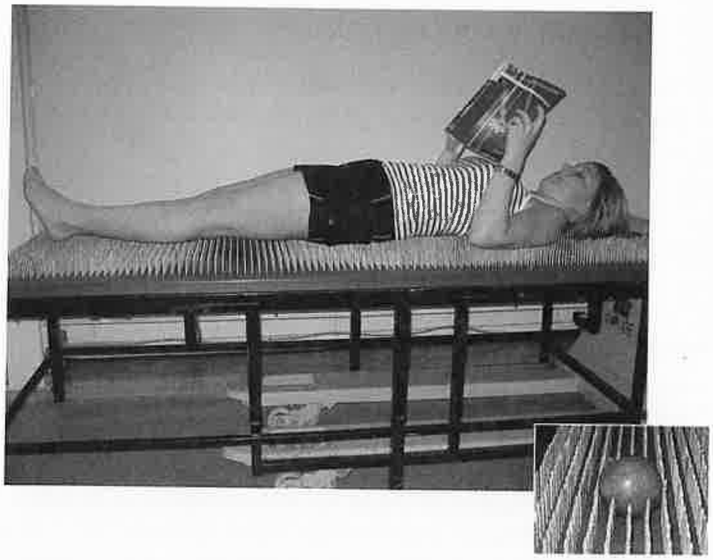


FIGURE 13.2

Physicist Sarah Blomberg lies without harm on the bed of nails because her weight is distributed over hundreds of nails, which makes the pressure at the point of each nail safely small. The inset photo of the dropped apple attests to the sharpness of the nails.

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[1] Pressure may be measured in any unit of force divided by any unit of area. The standard international (SI) unit of pressure, the newton per square meter, is called the *pascal* (Pa). A pressure of 1 Pa is very small and approximately equals the pressure exerted by a dollar bill resting flat on a table. Science types more often use kilopascals (1 kPa = 1000 Pa).

fyi

- Molecules that make up a liquid can flow by sliding over one another. A liquid takes the shape of its container. Its molecules are close together and greatly resist compressive forces, so liquids, like solids, are difficult to compress.

Pressure in a Liquid

When you swim under water, you can feel the water pressure acting against your eardrums. The deeper you swim, the greater the pressure. The pressure you feel is due to the weight of water above you. As you swim deeper, there is more water above you and therefore greater pressure. The pressure a liquid exerts depends on its depth.

Liquid pressure also depends on the density of the liquid. If you were submerged in a liquid more dense than water, the pressure would be correspondingly greater. The pressure due to a liquid is precisely equal to the product of weight density and depth:[2]

$$\text{Liquid pressure} = \text{weight density} \times \text{depth}$$

Simply put, the pressure a liquid exerts against the sides and bottom of a container depends on the density and the depth of the liquid. If we neglect atmospheric pressure, at twice the depth, the liquid pressure against the bottom is twice as great; at three times the depth, the liquid pressure is threefold; and so on. Or, if the liquid is two or three times as dense, the liquid pressure is correspondingly two or three times as great for any given depth. Liquids are practically incompressible—that is, their volume can hardly be changed by pressure (water volume decreases by only 50 millionths of its original volume for each atmosphere increase in pressure). So, except for small changes produced by temperature, the density of a particular liquid is practically the same at all depths.[3]

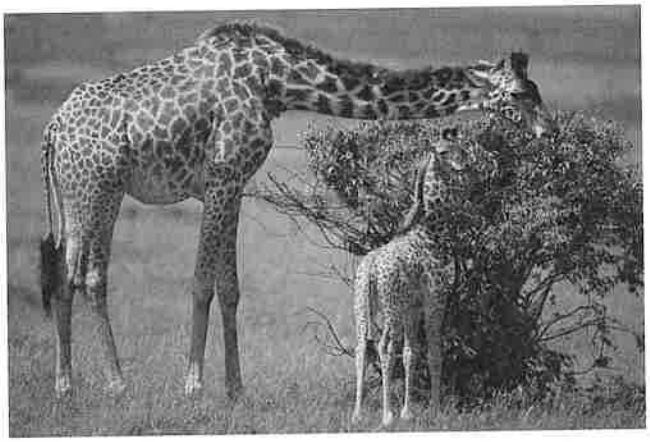

FIGURE 13.3

The dependence of liquid pressure on depth is not a problem for the giraffe because of its large heart and its intricate system of valves and elastic, absorbent blood vessels in the brain. Without these structures, the giraffe would faint when suddenly raising its head, and it would be subject to brain hemorrhaging when lowering it.

If you press your hand against a surface, and somebody else presses against your hand in the same direction, then the pressure against the surface is greater than if you pressed alone. Likewise with the atmospheric pressure that presses on the sur-

---

[2] This is derived from the definitions of pressure and weight density. Consider an area at the bottom of a vessel of liquid. The weight of the column of liquid directly above this area produces pressure. From the definition

$$\text{Weight density} = \frac{\text{weight}}{\text{volume}}$$

we can express this weight of liquid as

$$\text{Weight} = \text{weight density} \times \text{volume}$$

where the volume of the column is simply the area multiplied by the depth. Then we get

$$\text{Pressure} = \frac{\text{force}}{\text{area}} = \frac{\text{weight}}{\text{area}} = \frac{\text{weight density} \times \text{volume}}{\text{area}} = \frac{\text{weight density} \times (\cancel{\text{area}} \times \text{depth})}{\cancel{\text{area}}}$$
$$= \text{weight density} \times \text{depth}$$

For total pressure, we add to this equation the pressure due to the atmosphere on the surface of the liquid.

[3] The density of freshwater is 1000 kg/m^3. Since the weight (mg) of 1000 kg is 1000 × 10 N/kg = 10,000 N, the weight density of water is 10,000 newtons per cubic meter (or more precisely, 9800 N/m^3, using $g = 9.8$ N/kg). The water pressure beneath the surface of a lake is simply equal to this density multiplied by the depth in meters. For example, water pressure is 10,000 N/m^2 at a depth of 1 m and 100,000 N/m^2 at a depth of 10 m. In SI units, pressure is measured in pascals, so this would be 10,000 Pa and 100,000 Pa, respectively; or, in kilopascals, 10 kPa and 100 kPa, respectively. For the *total pressure* in these cases, add the pressure of the atmosphere, 101.3 kPa.

face of a liquid. The total pressure of a liquid, then, is weight density × depth *plus* the pressure of the atmosphere. When this distinction is important, we will use the term *total pressure.* Otherwise, our discussions of liquid pressure refer to pressure without regard to the normally ever-present atmospheric pressure. (You will learn more about atmospheric pressure in the next chapter.)

It is important to recognize that the pressure does not depend on the *amount* of liquid present. Volume is not the key—depth is. The average water pressure acting against a dam depends on the average *depth* of the water and not on the volume of water held back, as shown in Figure 13.4.

fyi

- Earth is the only planet in the solar system with a mostly liquid surface—its oceans. If Earth were a little closer to the Sun, the oceans would turn to vapor. If Earth were a little farther away, most of its surface, not just the polar regions, would be solid ice. It's nice that Earth is located where it is.

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Video

Dam

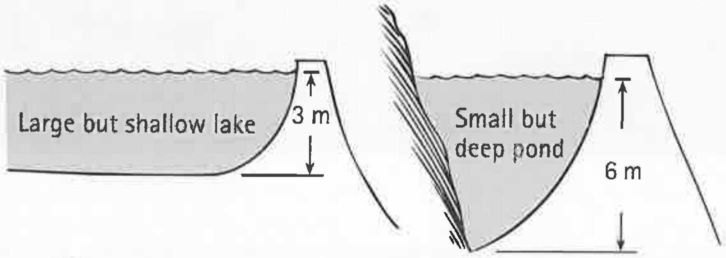

FIGURE 13.4

The large, shallow lake exerts only one-half the average pressure that the small, deep pond exerts.

You'll feel the same pressure whether you dunk your head a meter beneath the surface of the water in a small pool or to the same depth in the middle of a large lake. The same is true for a fish. Refer to the connecting vases in Figure 13.5. If we hold a goldfish by its tail and dunk its head a couple of centimeters under the surface, the water pressure on the fish's head will be the same in any of the vases. If we release the fish and it swims a few centimeters deeper, the pressure on the fish will increase with depth and be the same no matter which vase the fish is in. If the fish swims to the bottom, the pressure will be greater, but it makes no difference what vase it swims in. All vases are filled to equal depths, so the water pressure is the same at the bottom of each vase, regardless of its shape or volume. If water pressure at the bottom of a vase were greater than water pressure at the bottom of a neighboring narrower vase, the greater pressure would force water sideways and then up the narrower vase to a higher level until the pressures at the bottom were equalized. But this doesn't happen. Pressure is depth dependent, not volume dependent, so we see that there is a reason why water seeks its own level.

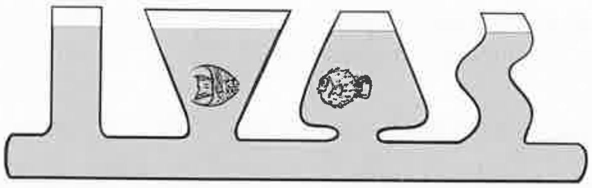

FIGURE 13.5

Liquid pressure is the same for any given depth below the surface, regardless of the shape of the containing vessel. Liquid pressure = weight density × depth (for total pressure add the air pressure at the top).

The fact that water seeks its own level can be demonstrated by filling a garden hose with water and holding the two ends at the same height. The water levels will be equal. If one end is raised higher than the other, water will flow out of the lower end, even if it has to flow "uphill" part of the way. This fact was not fully understood by some of the early Romans, who built elaborate aqueducts with tall arches and roundabout routes to ensure that water would always flow slightly downward every place along its route from the reservoir to the city. If pipes were laid in the ground and followed the natural contour of the land, in some places the water

fyi

- Not all Romans in ancient times believed that water couldn't flow uphill, as evidenced by some pipe systems back then that ran upward as well as downward.

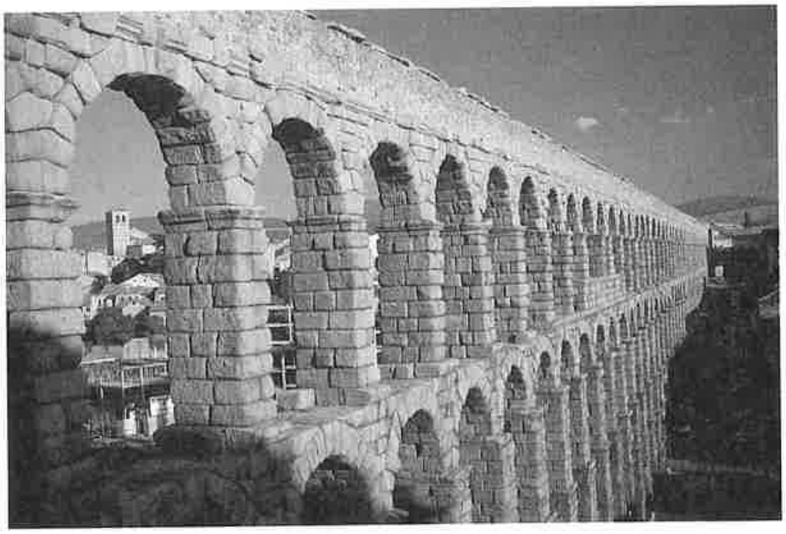

FIGURE 13.6
Roman aqueducts assured that water flowed slightly downhill from reservoir to city.

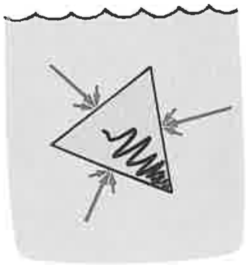

FIGURE 13.7
The forces of a liquid pressing against a surface add up to a net force that is perpendicular to the surface.

would have to flow uphill, and the Romans were skeptical of this. Careful experimentation was not yet the mode, so, with plentiful slave labor, the Romans built unnecessarily elaborate aqueducts.

An experimentally determined fact about liquid pressure is that it is exerted equally in all directions. For example, if we are submerged in water, no matter which way we tilt our heads we feel the same amount of water pressure on our ears. Because a liquid can flow, the pressure isn't only downward. We know pressure acts sideways when we see water spurting sideways from a leak in the side of an upright can. We know pressure also acts upward when we try to push a beach ball beneath the surface of the water. The bottom of a boat is certainly pushed upward by water pressure.

When liquid presses against a surface, there is a net *force* that is *perpendicular* to the surface. Although pressure doesn't have a specific direction, force does. Consider the triangular block in Figure 13.7. Focus your attention only at the three points midway along each surface. Water is forced against each point from many directions, only a few of which are indicated. Components of the forces that are not perpendicular to the surface cancel each other out, leaving only a net perpendicular force at each point.

That's why water spurting from a hole in a bucket initially exits the bucket in a direction at right angles to the surface of the bucket in which the hole is located. Then it curves downward due to gravity. The force exerted by a fluid on a smooth surface is always at right angles to the surface.[4]

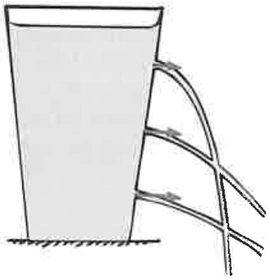

FIGURE 13.8
The force vectors act perpendicularly to the inner container surface and increase with increasing depth.

CHECK POINT

Suppose that when standing on a bathroom scale you raise one foot. Does the pressure you exert on the scale change? Is there a difference in the scale reading?

Check Your Answers

When you shift your weight by standing on one foot, pressure on the scale doubles. But the scale doesn't measure pressure—it measures weight. Except for some jiggling as you shift your weight, the scale reading stays the same.

---

[4] The speed of liquid out of the hole is $\sqrt{2gh}$, where h is the depth below the free surface. Interestingly, this is the same speed the water (or anything else) would acquire if freely falling the same vertical distance h.

Buoyancy

Anyone who has ever lifted a heavy submerged object out of water is familiar with *buoyancy,* the apparent loss of weight experienced by objects submerged in a liquid. For example, lifting a large boulder off the bottom of a riverbed is a relatively easy task as long as the boulder is below the surface. When it is lifted above the surface, however, the force required to lift it is increased considerably. This is because, when the boulder is submerged, the water exerts an upward force on it that is exactly opposite to the direction of gravity's pull. This upward force is called the **buoyant force,** and it is a consequence of pressure increasing with depth. Figure 13.9 shows why the buoyant force acts upward. Forces due to water pressures are exerted everywhere against the boulder in a direction perpendicular to its surface, as shown by the vectors. Force vectors against the sides at equal depths cancel one another, so there is no horizontal buoyant force. Force vectors in the vertical direction, however, don't cancel. Pressure is greater against the bottom of the boulder because the bottom is deeper. So upward forces against the bottom are greater than downward forces against the top, producing a net force upward—the buoyant force.

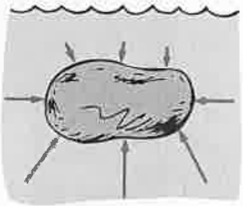

FIGURE 13.9

INTERACTIVE FIGURE

The greater pressure against the bottom of a submerged object produces an upward buoyant force.

Understanding buoyancy requires understanding the expression "volume of water displaced." If a stone is placed in a container that is brimful of water, some water will overflow (Figure 13.10). Water is *displaced* by the stone. A little thought will tell us that the *volume of the stone*—that is, the amount of space it takes up—is equal to the *volume of the water displaced.* If you place any object in a container partly filled with water, the level of the surface rises (Figure 13.11). By how much? By exactly the same amount as if a volume of water were poured in that equals the volume of the submerged object. This is a good method for determining the volume of irregularly shaped objects: *A completely submerged object always displaces a volume of liquid equal to its own volume.*

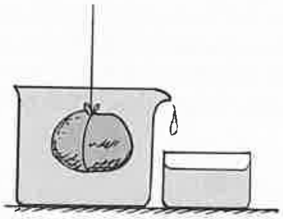

FIGURE 13.10

When a stone is submerged, it displaces water that has a volume equal to the volume of the stone.

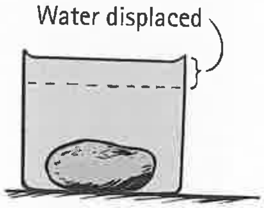

FIGURE 13.11

The increase in water level is the same as if you poured in a volume of water equal to the stone's volume.

CHECK POINT

A recipe calls for a specific amount of butter. How does the displacement method relate to the use of a kitchen measuring cup?

Check Your Answer

Put some water in the cup before you add the butter. Note the water-level reading on the side of the cup. Then add the butter and you'll note the water level rise. Because butter floats, poke it beneath the surface. When you subtract the lower-level reading from the higher-level reading, you know not only the volume of water displaced, but the volume of the butter.

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Buoyancy

Archimedes' Principle

The relationship between buoyancy and displaced liquid was first discovered in the 3rd century BC by the Greek scientist Archimedes. It is stated as follows:

An immersed object is buoyed up by a force equal to the weight of the fluid it displaces.

This relationship is called **Archimedes' principle.** It is true of liquids and gases, both of which are fluids. If an immersed object **displaces** 1 kg of fluid, the buoyant force acting on it is equal to the weight of 1 kg.[5] By *immersed,* we mean either *completely* or

If you stick your foot in water, it's immersed. If you jump in and sink and immersion is total, you're submerged.

---

[5] In lab, you may find it convenient to express buoyant force in kilograms, even though a kilogram is a unit of mass and not a unit of force. So, strictly speaking, the buoyant force is the *weight* of 1 kg, which is 10 N (or precisely, 9.8 N). Or we could as well say that the buoyant force is 1 *kilogram weight,* not simply 1 kg.

CHECK POINT

1. Two solid blocks of identical size are submerged in water. One block is lead and the other is aluminum. Upon which is the buoyant force greater?
2. If a fish makes itself denser, it will sink; if it makes itself less dense, it will rise. In terms of buoyant force, why is this so?

Check Your Answers

1. The buoyant force is the same on each block because they displace the same volume of water. For submerged objects, buoyant force is determined only by the volume of water displaced, not the object's weight.
2. When the fish decreases its volume, it displaces less water, so the buoyant force decreases. When the fish expands its volume, the buoyant force increases.

Flotation

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Flotation

Primitive peoples made their boats of wood. Could they have conceived of an iron ship? We don't know. The idea of floating iron might have seemed strange. Today it is easy for us to understand how a ship made of iron can float.

Consider a 1-ton block of solid iron. Because iron is nearly 8 times denser than water, it displaces only 1/8 ton of water when submerged, which is not enough to keep it afloat. Suppose we reshape the same iron block into a bowl (Figure 13.16). It still weighs 1 ton. But when we put it in water, it displaces a greater volume of water than when it was a block. The deeper the iron bowl is immersed, the more water it displaces and the greater the buoyant force acting on it. When the buoyant force equals 1 ton, it will sink no farther.

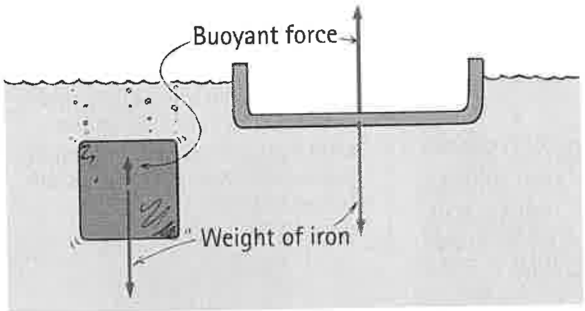


FIGURE 13.16

An iron block sinks, while the same quantity of iron shaped like a bowl floats.

When any boat displaces a weight of water equal to its own weight, it floats. This is sometimes called the **principle of flotation:**

A floating object displaces a weight of fluid equal to its own weight.

Every ship, every submarine, and every blimp must be designed to displace a weight of fluid equal to its own weight. Thus, a 10,000-ton ship must be built wide enough to displace 10,000 tons of water before it sinks too deep in the water. The same holds true for vessels in air. A blimp that weighs 100 tons displaces at least 100 tons of air. If it displaces more, it rises; if it displaces less, it falls. If it displaces exactly its weight, it hovers at constant altitude.

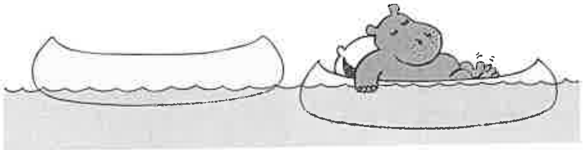


FIGURE 13.17

The weight of a floating object equals the weight of the water displaced by the submerged part.

For a given volume of displaced fluid, a denser fluid exerts a greater buoyant force than a less dense fluid. A ship, therefore, floats higher in saltwater than in freshwater because saltwater is slightly denser. Similarly, a solid chunk of iron will float in mercury, even though it will sink in water.

The physics of Figure 13.18 is nicely employed by the Falkirk Wheel, a unique rotating boat lift that replaced a series of 11 locks in Scotland. Connected to its 35-m tall wheel are two caissons brimful of water. When one or more boats enters a caisson, the amount of water that overflows weighs exactly as much as the boat(s). So the water-filled caissons always weigh the same whether or not they carry boats and the wheel always remains balanced. Therefore, in spite of its enormous mass, the wheel rotates each half revolution with very little power input.

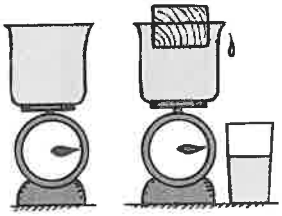


FIGURE 13.18

A floating object displaces a weight of fluid equal to its own weight.

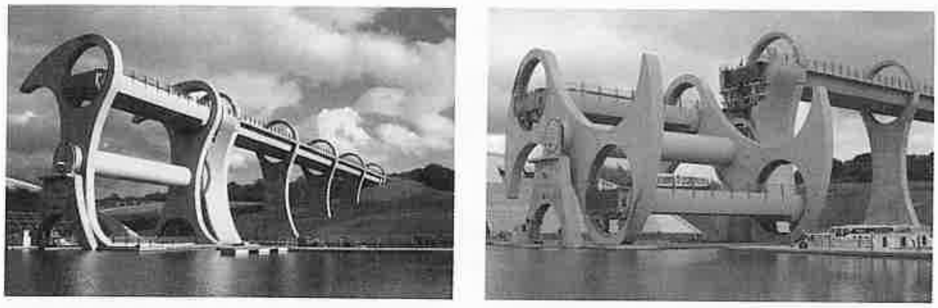


FIGURE 13.19

The Falkirk Wheel has two balanced water-filled caissons, one going up and one going down. The caissons rotate as the wheel turns so the water and boats don't tip out.

CHECK POINT

1. Why is it easier for you to float in saltwater than in freshwater?
2. On a boat ride, the skipper gives you a life preserver filled with lead pellets. When he sees the skeptical look on your face, he says that you'll experience a greater buoyant force if you fall overboard than your friends who wear Styrofoam-filled life preservers. Is he being truthful?

Check Your Answers

1. Saltwater is denser than freshwater, which means you don't "sink" as far when displacing your weight. You'd float even higher in mercury (density 13.6 g/cm^3), and you'd sink completely in alcohol (density 0.8 g/cm^3).
2. He's truthful. But what he doesn't tell you is that you'll drown! Your life preserver will submerge and displace more water than those of your friends who float at the surface. Although the buoyant force on you will be greater, your increased weight is greater still! Whether you float or sink depends on whether or not the buoyant force equals your weight.

Only in the special case of floating does the buoyant force acting on an object equal the object's weight.

Floating Mountains

The tip of a floating iceberg above the ocean's surface is approximately 10% of the whole iceberg. That's because ice is 0.9 times the density of water, so 90% of it submerges in water. Similarly, a mountain floats on the Earth's semiliquid mantle with only its tip showing. That's because Earth's continental crust is about 0.85 times the density of the mantle it floats upon; thus, about 85% of a mountain extends beneath the Earth's surface. So, like floating icebergs, mountains are appreciably deeper than they are high.

There is an interesting gravitational sidelight to this: Recall, from Chapter 9, that the gravitational field at the Earth's surface varies slightly with varying densities of underlying rock (which is valuable information to geologists and oil prospectors), and that gravitation is less at the top of a mountain because of the greater distance to Earth's center. Combining these ideas, we see that because the bottom of a mountain extends deep into the Earth's mantle, there is increased distance between a mountaintop and the denser mantle. This increased "gap" further reduces gravitation at the top of a mountain.

Another interesting fact about mountains: If you could shave off the top of an iceberg, the iceberg would be lighter and would be buoyed up to nearly its original height before being shaved. Similarly, when mountains erode, they are lighter, and they are pushed up from below to float to nearly their original heights. So, when a kilometer of mountain erodes away, some 85% of a kilometer of mountain thrusts up from below. That's why it takes so long for mountains to weather away.

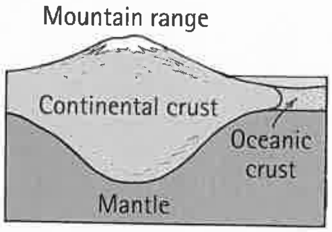


FIGURE 13.20

The continental crust is deeper beneath mountains.

CHECK POINT

A river barge loaded with gravel approaches a low bridge that it cannot quite pass under. Should gravel be removed *from* or added *to* the barge?

Check Your Answer

Ho, ho, ho! Do you think ol' Hewitt is going to give *all* the answers to Check Point questions? Good teaching is asking good questions, not providing all answers. You're on your own with this one!

Pascal's Principle

One of the most important facts about fluid pressure is that a change in pressure at one part of the fluid will be transmitted undiminished to other parts. For example, if the pressure of city water is increased at the pumping station by 10 units of pressure, the pressure everywhere in the pipes of the connected system will be increased by 10 units of pressure (provided that the water is at rest). This rule, discovered in the 17th century by Blaise Pascal, is called **Pascal's principle:**

> **A change in pressure at any point in an enclosed fluid at rest is transmitted undiminished to all points in the fluid.**

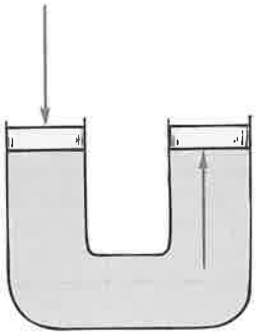


FIGURE 13.21

The force exerted on the left piston increases the pressure in the liquid and is transmitted to the right piston.

Fill a U-tube with water and place pistons at each end, as shown in Figure 13.21. Pressure exerted against the left piston will be transmitted throughout the liquid and against the bottom of the right piston. (The pistons are simply "plugs" that can slide freely but snugly inside the tube.) The pressure that the left piston exerts against the water will be exactly equal to the pressure the water exerts against the right piston. This is nothing to write home about. But suppose you make the tube on the right side wider and use a piston of larger area: Then the result will be impressive. In Figure 13.22 the piston on the right has 50 times the area of the piston on the left (let's say that the left piston has a cross-sectional area of 100 square centimeters and that the right piston has a cross-sectional area of 5000 square centimeters). Suppose a 10-kg load is placed on the left piston. Then an additional pressure (nearly 1 N/cm^2) due to the weight of the load is transmitted throughout the liquid and up against the larger piston. Here is where the difference between force and pressure comes in. The additional pressure is exerted against every square centimeter of the larger piston. Since there is 50 times the area, 50 times as much force is exerted on the larger piston. Thus, the larger piston will support a 500-kg load—50 times the load on the smaller piston!

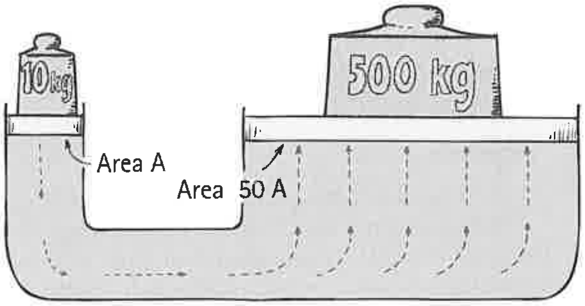


FIGURE 13.22

A 10-kg load on the left piston will support 500 kg on the right piston.

This *is* something to write home about, for we can multiply forces using such a device. One newton input produces 50 newtons output. By further increasing the area of the larger piston (or reducing the area of the smaller piston), we can multiply force, in principle, by any amount. Pascal's principle underlies the operation of the hydraulic press.

The hydraulic press does not violate energy conservation, because a decrease in distance moved compensates for the increase in force. When the small piston in Figure 13.22 is moved downward 10 centimeters, the large piston will be raised only one-fiftieth of this, or 0.2 centimeter. The input force multiplied by the distance moved by the smaller piston is equal to the output force multiplied by the distance moved by the larger piston; this is one more example of a simple machine operating on the same principle as a mechanical lever.

Pascal's principle applies to all fluids, whether gases or liquids. A typical application of Pascal's principle for gases and liquids is the automobile lift seen in many service stations (Figure 13.23). Increased air pressure produced by an air compressor is transmitted through the air to the surface of oil in an underground reservoir. The oil, in turn, transmits the pressure to a piston, which lifts the automobile. The relatively low pressure that exerts the lifting force against the piston is about the same as the air pressure in automobile tires.

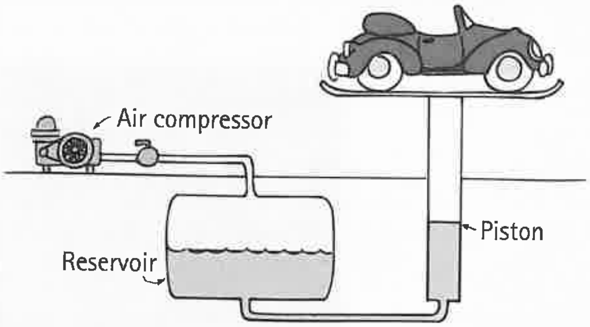


FIGURE 13.23

Pascal's principle in a service station.

Hydraulics is employed by modern devices ranging from very small to enormous. Note the hydraulic pistons in almost all construction machines where heavy loads are involved. The many applications of Pascal's principle have truly changed the landscape of our world.

FIGURE 13.24

Pascal's principle at work in the hydraulic devices on these incredible machines. We can only wonder whether Pascal envisioned the extent to which his principle would lead to the lifting of huge loads so easily.

CHECK POINT

1. As the automobile in Figure 13.23 is being lifted, how does the change in oil level in the reservoir compare with the distance the automobile moves?
2. If a friend commented that a hydraulic device is a common way of multiplying energy, what would you say?

Check Your Answers

1. The car moves up a greater distance than the oil level drops, since the area of the piston is smaller than the surface area of the oil in the reservoir.
2. No, no, no! Although a hydraulic device, like a mechanical lever, can multiply *force*, it always does so at the expense of distance. Energy is the product of force and distance. If you increase one, you decrease the other. No device has ever been found that can multiply energy!

Surface Tension

Suppose that you suspend a bent piece of clean wire from a sensitive spiral spring (Figure 13.25), lower the wire into water, and then raise it. As you attempt to free the wire from the water surface, you see from the stretched spring

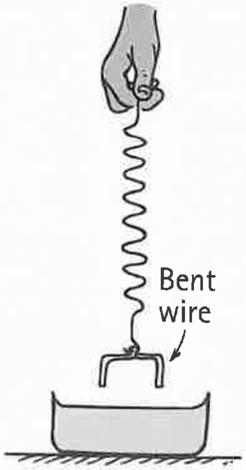


FIGURE 13.25

When the bent wire is lowered into the water and then raised, the spring will stretch because of surface tension.

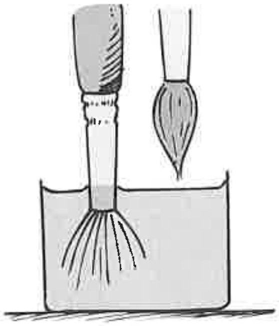


FIGURE 13.26

When the brush is taken out of the water, the hairs are held together by surface tension.

that the water surface exerts an appreciable force on the wire. The water surface resists being stretched, for it has a tendency to contract. You can also see this when a fine-haired paintbrush is wet. When the brush is under water, the hairs are fluffed pretty much as they are when the brush is dry, but when the brush is lifted out, the surface film of water contracts and pulls the hairs together (Figure 13.26). This contractive tendency of the surface of liquids is called **surface tension.**

Surface tension accounts for the spherical shape of liquid drops. Raindrops, oil drops, and falling drops of molten metal are all spherical because their surfaces tend to contract and force each drop into the shape having the least surface area. This is a sphere, the geometrical figure that has the least surface area for a given volume. For this reason, the mist and dewdrops on spider webs or on the downy leaves of plants are nearly spherical blobs. (The larger they are, the more gravity will flatten them.)

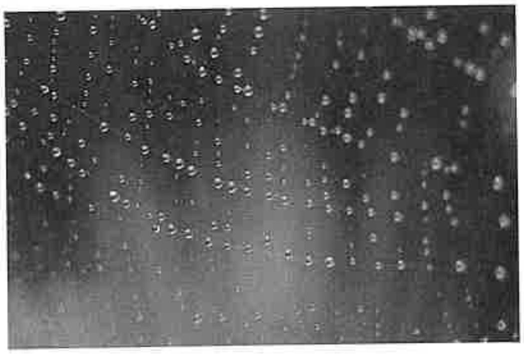


FIGURE 13.27

Small blobs of water are drawn by surface tension into spherelike shapes.

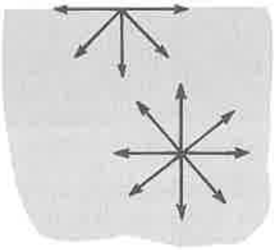


FIGURE 13.28

A molecule at the surface is pulled only sideways and downward by neighboring molecules. A molecule beneath the surface is pulled equally in all directions.

Surface tension is caused by molecular attractions. Beneath the surface, each molecule is attracted in every direction by neighboring molecules, resulting in no tendency to be pulled in any specific direction. A molecule on the surface of a liquid, however, is pulled only by neighbors on each side and downward from below; there is no pull upward (Figure 13.28). These molecular attractions thus tend to pull the molecule from the surface into the liquid, and this tendency minimizes the surface area. The surface behaves as if it were tightened into an elastic film. This is evident when dry steel needles or razor blades seem to float on water. They don't float in the usual sense, but they are supported by the surface molecules opposing an increase in surface area. The water surface sags like a piece of plastic wrap, which allows certain insects, such as water striders, to run across the surface of a pond.

The surface tension of water is greater than that of other common liquids, and pure water has a stronger surface tension than soapy water. We can see this when a little soap film on the surface of water is effectively pulled out over the entire surface. This minimizes the surface area of the water. The same thing happens for oil or grease floating on water. Oil has less surface tension than cold water, and it is drawn out into a film covering the whole surface. But hot water has less surface tension than cold water because the faster-moving molecules are not bonded as tightly. This allows the grease or oil in hot soups to float in little bubbles on the surface of the soup. When the soup cools and the surface tension of the water increases, the grease or oil is dragged out over the surface of the soup. The soup becomes "greasy." Hot soup tastes different from cold soup primarily because the surface tension of water in the soup changes with temperature.

Capillarity

When the end of a thoroughly clean glass tube with a small inside diameter is dipped into water, the water wets the inside of the tube and rises in it. In a tube with a bore of about 1/2 millimeter in diameter, for example, the water rises

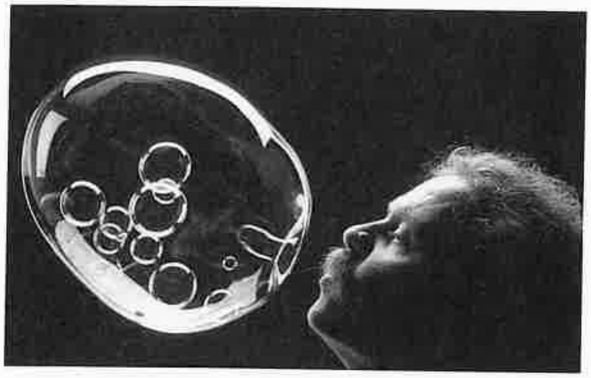


FIGURE 13.29

Bubble Master Tom Noddy blows bubbles within bubbles. The large bubble is elongated due to blowing, but it will quickly settle to a spherical shape due to surface tension.

slightly higher than 5 centimeters. With a still smaller bore, the water rises much higher (Figure 13.30). This rise of a liquid in a fine, hollow tube or in a narrow space is **capillarity.**

When thinking of capillarity, think of molecules as sticky balls. Water molecules stick to glass more than to each other. The attraction between unlike substances such as water and glass is called *adhesion.* The attraction between like substances, molecular stickiness, is called *cohesion.* When a glass tube is dipped into water, the adhesion between the glass and water causes a thin film of water to be drawn up over the inner and outer surfaces of the tube (Figure 13.31a). Surface tension causes this film to contract (Figure 13.31b). The film on the outer surface contracts enough to make a rounded edge. The film on the inner surface contracts more and raises water with it until the adhesive force is balanced by the weight of the water lifted (Figure 13.31c). In a narrower tube, the weight of the water in the tube is small and the water is lifted higher than it would be if the tube were wider.

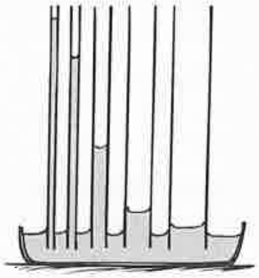


FIGURE 13.30

Capillary tubes.

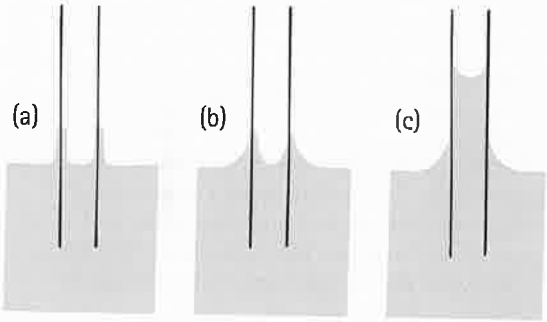


FIGURE 13.31

Hypothetical stages of capillary action, as seen in a cross-sectional view of a capillary tube.

If a paintbrush is dipped partway into water, the water will rise up into the narrow spaces between the bristles by capillary action. If your hair is long, let it hang into the sink or bathtub, and water will seep up to your scalp in the same way. This is how oil soaks upward in a lamp wick and water soaks into a bath towel when one end hangs in water. Dip one end of a lump of sugar in coffee, and the entire lump is quickly wet. Capillary action is essential for plant growth. It brings water to the roots of plants and transports sap and nourishment to high branches of trees. Just about everywhere we look, we can see capillary action at work. That's nice.

But from the point of view of an insect, capillarity is not so nice. Recall from the previous chapter that, because of an insect's relatively large surface area, it falls slowly in air. Gravity poses almost no risk at all—but not so with capillarity. Being in the grip of water may be fatal to an insect—unless it is equipped for water like a water strider.

SUMMARY OF TERMS

Pressure The ratio of force to the area over which that force is distributed:

$$\text{Pressure} = \frac{\text{force}}{\text{area}}$$

$$\text{Liquid pressure} = \text{weight density} \times \text{depth}$$

Buoyant force The net upward force that a fluid exerts on an immersed object.

Archimedes' principle An immersed body is buoyed up by a force equal to the weight of the fluid it displaces.

Principle of flotation A floating object displaces a weight of fluid equal to its own weight.

Pascal's principle The pressure applied to a motionless fluid confined in a container is transmitted undiminished throughout the fluid.

Surface tension The tendency of the surface of a liquid to contract in area and thus to behave like a stretched elastic membrane.

Capillarity The rise of a liquid in a fine, hollow tube or in a narrow space.

SUMMARY OF EQUATIONS

$$\text{Pressure} = \frac{\text{force}}{\text{area}}$$

$$\text{Liquid pressure} = \text{weight density} \times \text{depth}$$

REVIEW QUESTIONS

1. Give two examples of a fluid.

Pressure

2. Distinguish between *force* and *pressure.*

Pressure in a Liquid

3. What is the relationship between liquid pressure and the depth of a liquid? Between liquid pressure and density?
4. If you swim beneath the surface in saltwater, will the pressure be greater than in freshwater at the same depth? Why or why not?
5. How does water pressure 1 m below the surface of a small pond compare with water pressure 1 m below the surface of a huge lake?
6. If you punch a hole in a container filled with water, in what direction does the water initially flow outward from the container?

Buoyancy

7. Why does buoyant force act upward on an object submerged in water?
8. Why is there no horizontal buoyant force on a submerged object?
9. How does the volume of a completely submerged object compare with the volume of water displaced?

Archimedes' Principle

10. How does the buoyant force on a submerged object compare with the weight of water displaced?
11. Distinguish between a *submerged* body and an *immersed* body.
12. What is the mass of 1 L of water? What is its weight in newtons?
13. If a 1-L container is immersed halfway into water, what is the volume of water displaced? What is the buoyant force on the container?

What Makes an Object Sink or Float?

14. Is the buoyant force on a submerged object equal to the weight of the object itself or equal to the weight of the fluid displaced by the object?
15. There is a condition in which the buoyant force on an object does equal the weight of the object. What is this condition?
16. Does the buoyant force on a submerged object depend on the volume of the object or the weight of the object?
17. Fill in the blanks: An object denser than water will ______ in water. An object less dense than water will ______ in water. An object with the same density as water will ______ in water.
18. How is the density of a fish controlled? How is the density of a submarine controlled?

Flotation

19. It was emphasized earlier that buoyant force does not equal an object's weight but does equal the weight of displaced water. Now we say buoyant force equals the object's weight. Isn't this a grand contradiction? Explain.
20. Why do the caissons of the Falkirk Wheel (Figure 13.19) have the same weight whether or not they carry boats?

Pascal's Principle

21. What happens to the pressure in all parts of a confined fluid if the pressure in one part is increased?
22. If the pressure in a hydraulic press is increased by an additional 10 N/cm^2, how much extra load will the output piston support if its cross-sectional area is 50 cm^2?

Surface Tension

23. What geometrical shape has the least surface area for a given volume?
24. What is the cause of surface tension?

Capillarity

25. Distinguish between *adhesive* and *cohesive* forces.
26. What determines how high water will climb in a capillary tube?

PROJECTS

1. Place an egg in a pan of tap water. Then dissolve salt in the water until the egg floats. How does the density of an egg compare to that of tap water? To that of saltwater?
2. If you punch a couple of holes in the bottom of a water-filled container, water will spurt out because of water pressure. Now drop the container, and, as it freely falls, note that the water no longer spurts out! If your friends don't understand this, could you figure it out and then explain it to them?

3. Float a water-soaked Ping-Pong ball in a can of water held more than a meter above a rigid floor. Then drop the can. Careful inspection will show the ball was pulled beneath the surface as both the ball and the can drop. (What does this say about surface tension?) More dramatically, when the can makes impact with the floor, what happens to the ball, and why? Try it and you'll be astonished! (*Caution:* Unless you're wearing safety goggles, keep your head away from above the can when it makes impact.)
4. Soap greatly weakens the cohesive forces between water molecules. You can see this by adding some oil to a bottle of water and shaking it so that the oil and water mix. Notice that the oil and water quickly separate as soon as you stop shaking the bottle. Now add some liquid soap to the mixture. Shake the bottle again and you will see that the soap makes a fine film around each little oil bead and that a longer time is required for the oil to coalesce after you stop shaking the bottle. This is how soap works in cleaning. It breaks the surface tension around each particle of dirt so that the water can reach the particles and surround them. The dirt is carried away in rinsing. Soap is a good cleaner only in the presence of water.
5. Sprinkle some black pepper on the surface of some pure water in a saucer. The pepper floats. Add a drop of liquid dish soap to the surface and the pepper grains repel from the soap droplet. Stir gently once or twice and watch the pepper sink.

PLUG AND CHUG

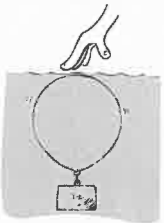
Pressure = weight density * depth

(Neglect the pressure due to the atmosphere in the following calculations.)

1. Calculate the water pressure at the bottom of the 100-m-high water tower shown in the photo that opens this chapter.
2. Calculate the water pressure at the base of the Hoover Dam. The depth of water behind the dam is 220 m.
3. The top floor of a building is 50 m above the basement. Calculate how much greater the water pressure is in the basement than on the top floor.
4. A 1-m-tall barrel is closed on top except for a thin pipe extending 5 m up from the top. When the barrel is filled with water up to the base of the pipe (1 m deep) the water pressure on the bottom of the barrel is 10 kPa. What is the pressure on the bottom when water is added to fill the pipe to its top?

RANKING

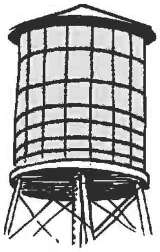
1. Rank the pressures from most to least for the following:
   a. Bottom of a 20-cm-tall container of saltwater.
   b. Bottom of a 20-cm-tall container of freshwater.
   c. Bottom of a 5-cm-tall container of mercury.
2. Rank the following from most to least for the percentage of its volume above the water line:
   a. Basketball floating in freshwater
   b. Basketball floating in saltwater
   c. Basketball floating in mercury
3. Think about what happens to the volume of an air-filled balloon on top of water, and beneath. Then rank the buoyant force on a weighted balloon in water, from most to least, when it is
   a. barely floating with its top at the surface.
   b. pushed 1 m beneath the surface.
   c. pushed 2 m beneath the surface.



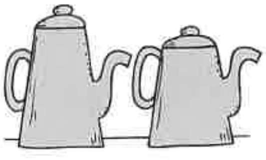
EXERCISES

1. What common liquid covers more than two-thirds of our planet, makes up 60% of our bodies, and sustains our lives and lifestyles in countless ways?
2. You know that a sharp knife cuts better than a dull knife. Do you know why this is so? Defend your answer.
3. Which is more likely to hurt—being stepped on by a 200-lb man wearing loafers or being stepped on by a 100-lb woman wearing high heels?
4. Which do you suppose exerts more pressure on the ground—a 5000-kg elephant or a 50-kg lady standing on spike heels? (Which will be more likely to make dents in a linoleum floor?) Approximate a rough calculation for each.
5. Why are persons who are confined to bed less likely to develop bedsores on their bodies if they rest on a waterbed rather than an ordinary mattress?
6. The photo shows physics instructor Marshall Ellenstein walking barefoot on broken glass bottles in his class. What physics concept is Marshall demonstrating, and why is he careful that the broken pieces are small and numerous? (The Band-Aids on his feet are for humor!)
7. Why is blood pressure measured in the upper arm, at the elevation of your heart?

8. Why does your body get more rest when you're lying down than when you're sitting? Is blood pressure in your legs greater?
9. When you are standing, blood pressure in your legs is greater than in your upper body. Would this be true for an astronaut in orbit? Defend your answer.
10. If water faucets upstairs and downstairs are turned fully on, will more water per second flow out of the upstairs faucets or the downstairs faucets?
11. How does water pressure 1 m beneath the surface of a lake compare with water pressure 1 m beneath the surface of a swimming pool?
12. The sketch shows a reservoir that supplies water to a farm. It is made of wood and is reinforced with metal hoops. (a) Why is it elevated? (b) Why are the hoops closer together near the bottom part of the tank?



13. Which teapot holds more liquid?



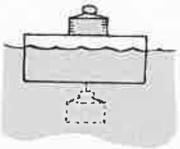
14. A block of aluminum with a volume of 10 cm^3 is placed in a beaker of water filled to the brim. Water overflows. The same is done in another beaker with a 10-cm^3 block of lead. Does the lead displace more, less, or the same amount of water?
15. A block of aluminum with a mass of 1 kg is placed in a beaker of water filled to the brim. Water overflows. The same is done in another beaker with a 1-kg block of lead. Does the lead displace more, less, or the same amount of water?
16. A block of aluminum with a weight of 10 N is placed in a beaker of water filled to the brim. Water overflows. The same is done in another beaker with a 10-N block of lead. Does the lead displace more, less, or the same amount of water? (Why are your answers to this exercise and to Exercise 15 different from your answer to Exercise 14?)
17. In 1960, the U.S. Navy's bathyscaphe *Trieste* (a submersible) descended to a depth of nearly 11 km in the Marianas Trench near the Philippines in the Pacific Ocean. Instead of a large viewing window, it had a small circular window 15 cm in diameter. What is your explanation for so small a window?
18. There is a legend of a Dutch boy who bravely held back the whole North Sea by plugging a hole in a dike with his finger. Is this possible and reasonable? (See also Problem 4.)
19. There is a story about Pascal's assistant climbing a ladder and pouring a small container of water into a tall, thin, vertical pipe inserted into a wooden barrel full of water below. The barrel burst when the water in the pipe reached about 12 m. This was all the more intriguing because the weight of added water in the tube was very small. What is your explanation, and how does this relate to Plug-and-Chug 4?
20. If you've wondered about the flushing of toilets on the upper floors of city skyscrapers, how do you suppose the plumbing is designed so that there is not an enormous impact of sewage arriving at the basement level? (Check your speculations with someone who is knowledgeable about architecture.)
21. Why does water "seek its own level"?
22. Suppose that you wish to lay a level foundation for a home on hilly and bushy terrain. How can you use a garden hose filled with water to determine equal elevations for distant points?
23. When you are sunbathing on a stony beach, why do the stones hurt your feet less when you're standing in deep water?
24. If liquid pressure were the same at all depths, would there be a buoyant force on an object submerged in the liquid? Explain.
25. A can of diet soda floats in water, whereas a can of regular soda sinks. Explain this phenomenon first in terms of density, then in terms of weight versus buoyant force.
26. Why will a block of iron float in mercury but sink in water?
27. The mountains of the Himalayas are slightly less dense than the mantle material upon which they "float." Do you suppose that, like floating icebergs, they are deeper than they are high?
28. Why is a high mountain composed mostly of lead an impossibility on Earth?
29. How much force is needed to hold a nearly weightless but rigid 1-L carton beneath the surface of water?

30. Why will a volleyball held beneath the surface of water have more buoyant force than if it is floating?

31. Why does an inflated beach ball pushed beneath the surface of water swiftly shoot above the water surface when released?

32. Why is it inaccurate to say that heavy objects sink and that light objects float? Give exaggerated examples to support your answer.

33. Why is the buoyant force on a submerged submarine appreciably greater than the buoyant force on it while it is floating?



34. A piece of iron placed on a block of wood makes it float lower in the water. If the iron were instead suspended beneath the wood, would the wood float as low, lower, or higher? Defend your answer.

35. Compared with an empty ship, would a ship loaded with a cargo of Styrofoam sink deeper into the water or rise in the water? Defend your answer.

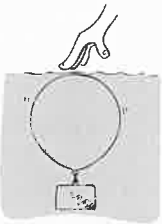
36. If a submarine starts to sink, will it continue to sink to the bottom if no changes are made? Explain.

37. A barge filled with scrap iron is in a canal lock. If the iron is thrown overboard, does the water level at the side of the lock rise, fall, or remain unchanged? Explain.

38. Would the water level in a canal lock go up or down if a battleship in the lock sank?

39. Will a rock gain or lose buoyant force as it sinks deeper in water? Or will the buoyant force remain the same at greater depths? Defend your answer.

40. Will a swimmer gain or lose buoyant force as she swims deeper in the water? Or will her buoyant force remain the same at greater depths? Defend your answer, and contrast it with your answer to Exercise 39.



41. A balloon is weighted so that it is barely able to float in water. If it is pushed beneath the surface, will it return to the surface, stay at the depth to which it is pushed, or sink? Explain. (*Hint:* Does the balloon's density change?)

42. The density of a rock doesn't change when it is submerged in water, but your density changes when you are submerged. Explain.

43. In answering the question of why bodies float higher in saltwater than in freshwater, your friend replies that the reason is that saltwater is denser than freshwater. (Does your friend often answer questions by reciting only factual statements that relate to the answers but don't provide any concrete reasons?) How would you answer the same question?

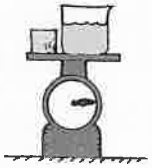
44. A ship sailing from the ocean into a freshwater harbor sinks slightly deeper into the water. Does the buoyant force on the ship change? If so, does it increase or decrease?

45. Suppose that you are given the choice between two life preservers that are identical in size, the first a light one filled with Styrofoam and the second a very heavy one filled with gravel. If you submerge these life preservers in the water, upon which will the buoyant force be greater? Upon which will the buoyant force be ineffective? Why are your answers different?

46. The weight of the human brain is about 15 N. The buoyant force supplied by fluid around the brain is about 14.5 N. Does this mean that the weight of fluid surrounding the brain is at least 14.5 N? Defend your answer.

47. The relative densities of water, ice, and alcohol are 1.0, 0.9, and 0.8, respectively. Do ice cubes float higher or lower in a mixed alcoholic drink? What comment can you make about a cocktail in which the ice cubes lie submerged at the bottom of the glass?

48. When an ice cube in a glass of water melts, does the water level in the glass rise, fall, or remain unchanged? Does your answer change if the ice cube has many air bubbles? How about if the ice cube contains many grains of heavy sand?



49. When the wooden block is placed in the beaker, what happens to the scale reading? Answer the same question for an iron block.

50. A small aquarium half-filled with water is on a spring scale. Will the reading of the scale increase or remain the same if a fish is placed in the aquarium? (Will your answer be different if the aquarium is initially filled to the brim?)

51. If the gravitational field of Earth were to increase, would a fish float to the surface, sink, or stay at the same depth?

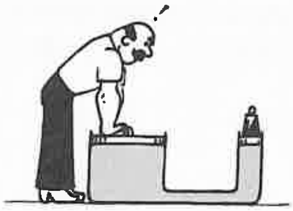
52. What would you experience when swimming in water in an orbiting space habitat where simulated gravity is g? Would you float in the water as you do on Earth?

53. We say that the shape of a liquid is that of its container. But, with no container and no gravity, what is the natural shape of a blob of water? Why?

54. If you release a Ping-Pong ball beneath the surface of water, it will rise to the surface. Would it do the same if it were inside a big blob of water floating weightless in an orbiting spacecraft?

55. So you're on a run of bad luck, and you slip quietly into a small, calm pool as hungry crocodiles lurking at the bottom are relying on Pascal's principle to help them to detect a tender morsel. What does Pascal's principle have to do with their delight at your arrival?

56. In the hydraulic arrangement shown, the larger piston has an area that is 50 times that of the smaller piston. The strong man hopes to exert enough force on the large piston to raise the 10 kg that rest on the small piston. Do you think he will be successful? Defend your answer.

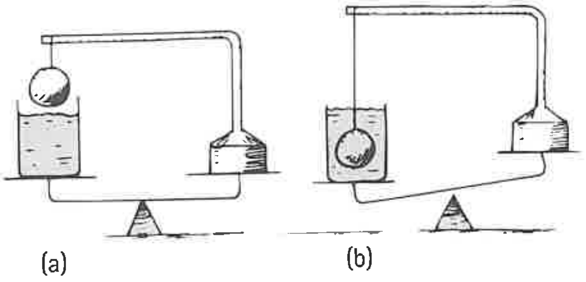


57. In the hydraulic arrangement shown in Figure 13.22, the multiplication of force is equal to the ratio of the areas of the large and small pistons. Some people are surprised to learn that the area of the liquid surface in the reservoir of the arrangement shown in Figure 13.23 is immaterial. What is your explanation to resolve this confusion?

58. Why will water flow more readily than cold water through small leaks in a car radiator?

59. A chunk of steel will sink in water. But a steel razor blade, carefully placed on the surface of water, will not sink. What is your explanation?

60. The weight of the container of water, as shown in (a), is equal to the weight of the stand and the suspended solid iron ball. When the suspended ball is lowered into the water, as shown in (b), the balance is upset. Challenge your friends and ask if the additional weight needed on the right side to restore balance is greater than, equal to, or less than the weight of the solid iron ball.



PROBLEMS

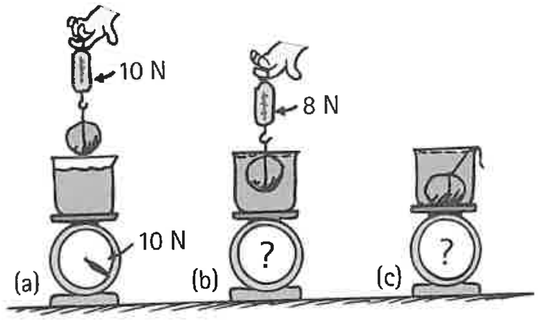
1. Calculate the average force per nail when Sarah (Figure 13.2), who weighs 120 pounds, lies on a bed of nails and is supported by 600 nails.

2. Suppose that you balance a 5-kg ball on the tip of your finger, which has an area of 1 cm^2. Show that the pressure on your finger is 50 N/cm^2, which is 500 kPa.

3. A 6-kg piece of metal displaces 1 L of water when submerged. Show that its density is 6000 kg/m^3. How does this compare with the density of water?

4. A dike in Holland springs a leak through a hole of area 1 cm^2 at a depth of 2 m below the water surface. How much force must a boy apply to the hole with his thumb to stop the leak? Could he do it?

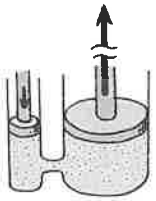
5. In lab you find that a 1-kg rock suspended above water weighs 10 N. When the rock is suspended beneath the surface of the water, the scale reads 8 N.



a. What is the buoyant force on the rock?
b. If the container of water weighs 10 N on the weighing scale, what is the scale reading when the rock is suspended beneath the surface of the water?
c. What is the scale reading when the rock is released and rests at the bottom of the container?

6. A merchant in Katmandu sells you a solid gold 1-kg statue for a very reasonable price. When you get home, you wonder whether or not you got a bargain, so you lower the statue into a container of water and measure the volume of displaced water. Show that, for pure gold, the volume of water displaced will be 51.8 cm^3.

7. In the sketch, the small hydraulic piston has a diameter of 2 cm. The large piston has a diameter of 6 cm. For each newton of force applied to the small piston, how many newtons of force are exerted by the large piston?



• **8.** Your friend of mass 100 kg can just barely float in freshwater. Calculate her approximate volume.

CHAPTER 13 ONLINE RESOURCES

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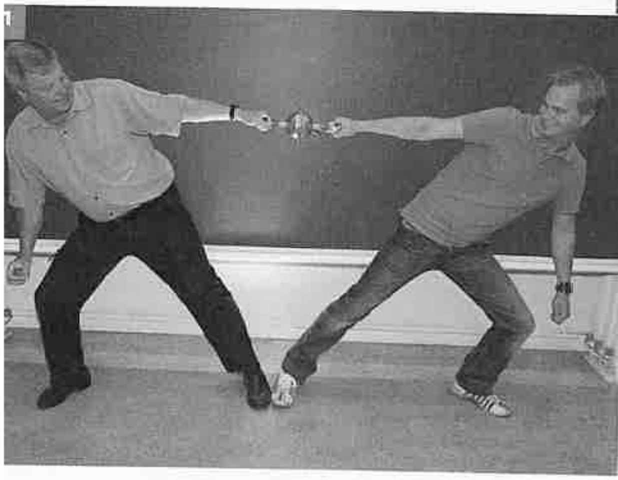

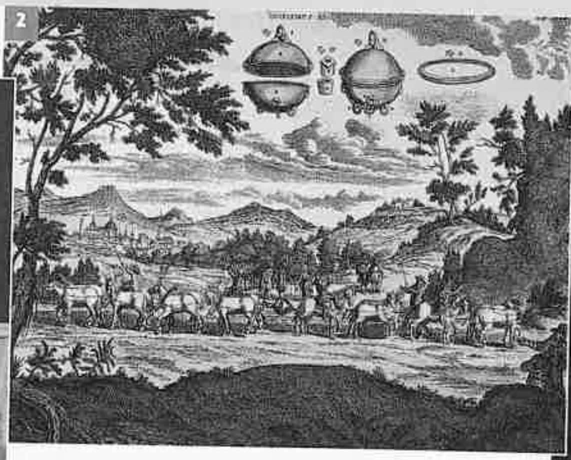

1 The forces due to atmospheric pressure are nicely shown by Swedish father-and-son physics professors, P. O. and Johan Zetterberg, who pull on a classroom model of the Magdeburg hemispheres. 2 A print shows the famous 1654 demonstration of atmospheric pressure with the original Magdeburg hemispheres. Two teams of horses couldn't pull the evacuated hemispheres apart. 3 Air in motion is a different story, as Maitreya Suchocki blows across the top of the paper reducing air pressure so that the slightly greater pressure beneath pushes the paper upward.

Can a vacuum, a condition of nothingness, exist? And how great is the pressure of air? In this chapter we'll learn how a German man in 1654 answered these questions. After inventing the first suction and air pumps that produced partial vacuums, he performed the widely attended and celebrated demonstration of the "Magdeburg hemispheres," as shown in the engraving above. He placed together two copper hemispheres about 1/2 meter in diameter to form a sphere, with an airtight joint composed of an oil-soaked leather gasket. When he evacuated the sphere with his vacuum pump, two teams of eight horses were unable to pull the hemispheres apart. (Some accounts say it took thirty horses to do the job.) Witnesses were astonished to see stunning evidence of the great force of the atmosphere. This man was Otto Guericke, later raised in rank to Otto von Guericke.

Like most successful scientists at the time, Guericke was born into a wealthy family. Except for benevolent benefactors, science as a profession back then didn't exist. People with time on their hands did science as a hobby, not unlike the way we play computer games today. At age 15, Guericke studied at Leipzig University in Germany. With the early stages of the Thirty Years War threatening, he and his family moved to Helmstedt, where he studied law. His studies were interrupted by the death of his father, whereupon Guericke moved to Leiden, Netherlands. He didn't complete any degree and instead went on a 9-month journey through France and England, as young men of noble houses were entitled to do.

Otto von Guericke continued his fascination with reduced air pressure. Influenced by the astronomy of Copernicus, he studied the nature of space and the possibility of empty space. Like his contemporaries Torricelli and Pascal (profiled at the beginning of the previous chapter), he became convinced that the height of the column of mercury in a barometer was a measure of air pressure. He made forecasts of the weather based on his observations over a period of years and proposed a network of stations to make systematic reports of the barometer readings and weather. He died in 1686 at the age of 83.

Interestingly, von Guericke's demonstration preceded knowledge of Newton's third law. The forces on the hemispheres would have been the same if he used only one team of horses and tied the other end of the rope to a tree!

The Atmosphere

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

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

The exact height of the atmosphere has no real meaning, for the air gets progressively thinner and thinner the higher one travels upward. Eventually, it thins out to emptiness in interplanetary space. Even in the vacuous regions of interplanetary space, however, there is a gas density of about one molecule per cubic centimeter. This is primarily hydrogen, the most plentiful element in the universe. About 50% of the atmosphere is below an altitude of 5.6 km (18,000 ft), 75% is below 11 km (36,000 ft), 90% is below 18 km (60,000 ft), and 99% is below about 30 km (100,000 ft) (Figure 14.1). A detailed description of the atmosphere can be found on various web sites.

fyi

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

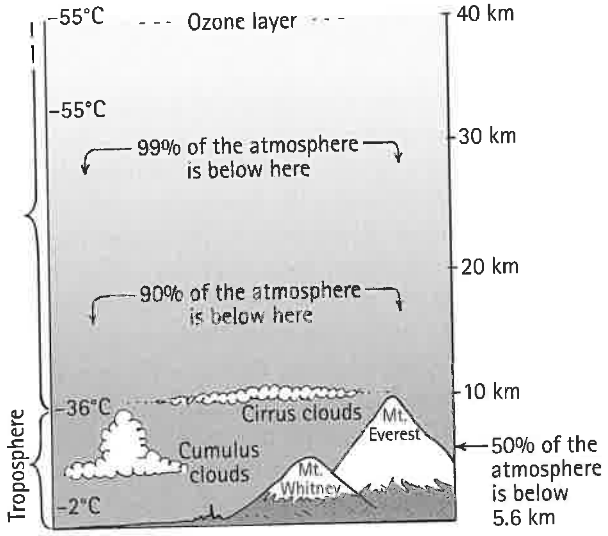

FIGURE 14.1

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

CHECK POINT

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

Check Your Answer

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

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

Atmospheric Pressure

We live at the bottom of an ocean of air. The atmosphere, much like water in a lake, exerts pressure. As mentioned at the beginning of this chapter, the strength of atmospheric pressure was convincingly demonstrated by Otto von Guericke. Similarly, when the air pressure inside a cylinder like the one shown in Figure 14.2 is reduced, there is an upward force on the piston from the air outside. This force is large enough to lift a heavy weight. If the inside diameter of the cylinder is 10 cm or greater, a person can be suspended by this force.

Contrary to common thought, what the experiment of Figure 14.2 does *not* show is "force of suction." If we say there is a force of suction, then we assume that a vacuum can exert a force. But what is a vacuum? It is an absence of matter; it is a condition of nothingness. How can nothing exert a force? The hemispheres in von Guericke's demonstration were not sucked together, nor is the piston holding the weight up in Figure 14.2 sucked upward. The hemispheres and the piston are pushed by the weight of the atmosphere.

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

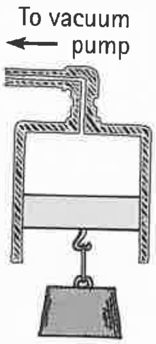

FIGURE 14.2

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

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

FIGURE 14.3

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

At sea level, 1 m^3 of air has a mass of about 1.25 kg. So the air in your kid sister's small bedroom weighs about as much as she does! The density of air decreases with altitude. At 10 km, for example, 1 m^3 of air has a mass of about 0.4 kg. To compensate for this, airplanes are pressurized; the additional air needed to fully pressurize a modern jumbo jet, for example, is more than 1000 kg. Air is heavy if you have enough of it. If your kid sister doesn't believe that air has weight, you can show her why she falsely perceives the air to be weight-free. If you hand her a plastic bag of water, she'll tell you that it has weight. But, if you hand her the same bag of water while she's submerged in a swimming pool, she won't feel its weight. That's because she and the bag are surrounded by water. Likewise with the air that is all around us.

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

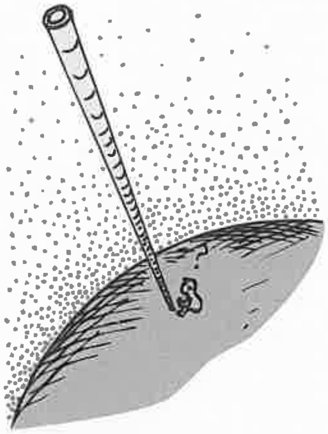

FIGURE 14.4

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

produces a pressure of 100,000 N/m^2—or, equivalently, 100,000 pascals, or 100 kilopascals. To be more exact, the average atmospheric pressure at sea level is 101.3 kilopascals (101.3 kPa).[1]

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

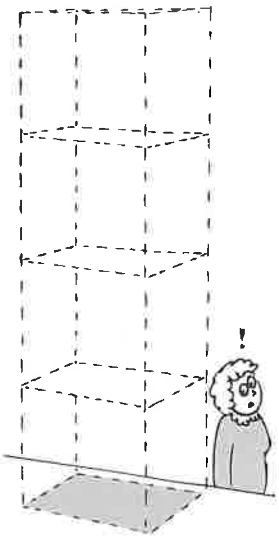

FIGURE 14.5

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

FIGURE 14.6

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

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Videos

Air Has Weight

Air Is Matter

CHECK POINT

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

Check Your Answers

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

TABLE 14.1

Densities of Various Gases

Gas	Density (kg/m^3)*
Dry air	
0°C	1.29
10°C	1.25
20°C	1.21
30°C	1.16
Hydrogen	0.090
Helium	0.178
Nitrogen	1.25
Oxygen	1.43

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

The Barometer

In 1643, Italian physicist and mathematician Evangelista Torricelli found a way to measure the pressure that air exerts—he invented the first **barometer.** A simple mercury barometer is illustrated in Figure 14.7. It consists of a mercury-filled

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

glass tube, somewhat longer than 76 cm, that is immersed in a dish (reservoir) of mercury. When Torricelli tipped the mercury-filled tube upside down and placed it mouth downward in a dish of mercury, the mercury in the tube dropped to a level where the weight of mercury in the tube was balanced by the atmospheric force exerted on the reservoir. The empty space trapped above, except for some mercury vapor, is a vacuum. The vertical height of the mercury column remains constant even when the tube is tilted, unless the top of the tube is less than 76 cm above the level in the dish—in which case the mercury completely fills the tube.

The balance of mercury in a barometer is similar to the way a playground seesaw will balance when the torques of people at its two ends are equal. The barometer "balances" when the weight of the liquid in the tube exerts the same pressure as the atmosphere outside. Whatever the width of the tube, a 76-cm column of mercury weighs the same as the air that would fill a super-tall 30-km tube of the same width. If the atmospheric pressure increases, then the atmosphere pushes down harder on the mercury and the column of mercury is pushed higher than 76 cm. The mercury is literally pushed up into the tube of a barometer by the weight of the atmosphere. Atmospheric pressure was originally measured in millimeters of mercury, easily read on a barometer. Today it is measured in kilopascals.

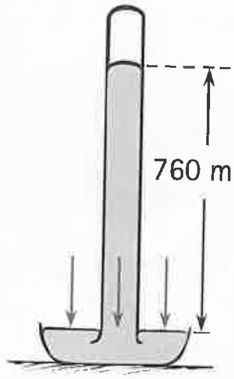


FIGURE 14.7

A simple mercury barometer.

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

FIGURE 14.8

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

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

If you understand these ideas, you can understand why there is a 10.3-m limit on the height that water can be lifted with vacuum pumps. The old-fashioned farm-type pump, like the one shown in Figure 14.9, operates by producing a partial vacuum in a pipe that extends down into the water below. The weight of the atmosphere on the surface of the water simply pushes the water up into the region of reduced pressure inside the pipe. Can you see that, even with a perfect vacuum, the maximum height to which water can be lifted is 10.3 m?

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

FIGURE 14.9

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

FIGURE 14.10

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

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

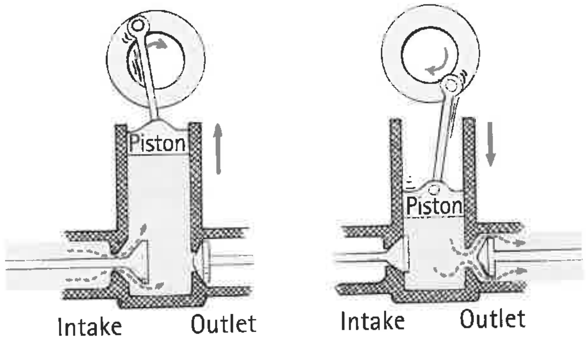
Vacuums are produced by pumps, which work by virtue of a gas tending to fill its container. If a space with less pressure is provided, gas will flow from the region of higher pressure to the region of lower pressure. A vacuum pump simply provides a region of lower pressure into which fast-moving gas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

fyi

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

FIGURE 14.11

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



CHECK POINT

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

Check Your Answer

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

Boyle's Law

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Video
Air Has Pressure

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

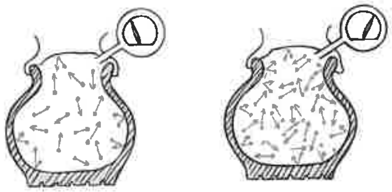

FIGURE 14.12

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

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

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

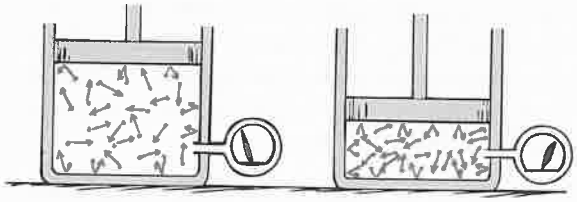

FIGURE 14.13
When the volume of gas is decreased, density and therefore pressure are increased.

Notice in these examples involving the piston that *pressure and volume are inversely proportional;* if you double one, for example, you halve the other:[2]

$$P_1V_1 = P_2V_2$$

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

$$_{P}V = P_{V}$$

In general, we can say that the product of pressure and volume for a given mass of gas is a constant as long as the temperature doesn't change. This relationship is called **Boyle's law,** after physicist Robert Boyle, who, with the help of fellow physicist Robert Hooke, made this discovery in the 17th century. Boyle's law applies to ideal gases. An ideal gas is one in which the disturbing effects of the forces between molecules and the finite size of the individual molecules can be neglected. Air and other gases under normal pressures approach ideal-gas conditions.

CHECK POINT

1. A piston in an airtight pump is withdrawn so that the volume of the air chamber is increased 3 times. What is the change in pressure?
2. A scuba diver 10.3 m deep breathes compressed air. If she were to hold her breath while returning to the surface, by how much would the volume of her lungs tend to increase?

Check Your Answers

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

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

fyi

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

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

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

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Video
Buoyancy of Air

Buoyancy of Air

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

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

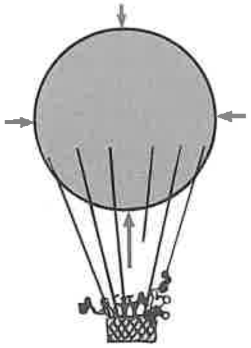

FIGURE 14.14

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

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

Greatest buoyancy would be achieved if a balloon were evacuated, but this isn't practical. The weight of a structure needed to keep an evacuated balloon from collapsing would more than offset the advantage of the extra buoyancy. So balloons are filled with gas less dense than ordinary air, which keeps the balloon from collapsing while keeping it light. In sport balloons, the gas is simply heated air. In balloons intended to reach very high altitudes or to stay up for a long time, helium is usually used. Its density is small enough so that the combined weight of helium, balloon, and whatever the cargo happens to be is less than the weight of the air it displaces.[3] Low-density gas is used in a balloon for the same reason that cork or Styrofoam is used in a swimmer's life preserver. The cork or Styrofoam possesses no strange tendency to be drawn toward the surface of water, and the gas possesses no strange tendency to rise. Both are buoyed upward like anything else. They are simply light enough for the buoyancy to be significant.

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

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

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[3] Hydrogen is the least dense gas, but, because it is highly flammable, it is seldom used.

weight is a little less than the weight of air displaced. When in motion, the ship may be raised or lowered by means of horizontal "elevators."

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

CHECK POINT

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

Check Your Answers

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

Bernoulli's Principle

Consider a continuous flow of water through a pipe. Because water doesn't "bunch up," the amount of water that flows past any given section of the pipe is the same as the amount that flows past any other section of the same pipe—even if the pipe widens or narrows. For continuous flow, a fluid speeds up when it goes from a wide to a narrow part of the pipe. This is evident in a broad, slow-moving river that flows more swiftly as it enters a narrow gorge. It is also evident when water flowing from a garden hose speeds up when you squeeze the end of the hose to make the stream narrower.

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

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

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

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

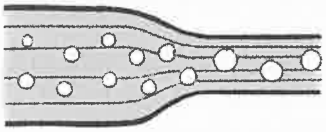

FIGURE 14.18

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

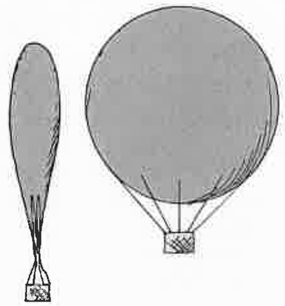

FIGURE 14.15

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

FIGURE 14.16

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

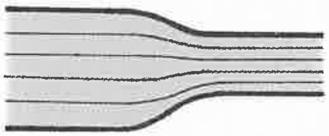

FIGURE 14.17

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

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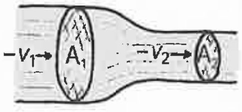
- Because the volume of water flowing through a pipe of different cross-sectional areas A remains constant, speed of flow v is high where the area is small, and the speed is low where the area is large. This is stated in the equation of continuity:

$$A_1v_1 = A_2v_2$$

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



Bernoulli's principle is a consequence of the conservation of energy, although, surprisingly, he developed it long before the concept of energy was formalized.[4] The full energy picture for a fluid in motion is quite complicated. Simply stated, more speed and kinetic energy mean less pressure, and more pressure means less speed and kinetic energy.

Recall from Chapter 6 that a large change in momentum is associated with a large impulse. So when water from a fireman's hose hits you, the impulse can knock you off your feet. Interestingly, the pressure *within* that water is relatively small!

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

The decrease of fluid pressure with increasing speed may at first seem surprising, particularly if you fail to distinguish between the pressure *within* the fluid, internal pressure, and the pressure *by* the fluid on something that interferes with its flow. Internal pressure within flowing water and the external pressure it can exert on whatever it encounters are two different pressures. When the momentum of moving water or anything else is suddenly reduced, the impulse it exerts is relatively huge. A dramatic example is the use of high-speed jets of water to cut steel in modern machine shops. The water has very little internal pressure, but the pressure the stream exerts on the steel interrupting its flow is enormous.

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

APPLICATIONS OF BERNOULLI'S PRINCIPLE

Hold a sheet of paper in front of your mouth, as shown in Figure 14.19. When you blow across the top surface, the paper rises. That's because the internal pressure of moving air across the curved top of the paper is less than the atmospheric pressure beneath it.

FIGURE 14.19

The paper rises when Tim blows across its top surface.

Anyone who has ridden in a convertible car with the canvas top up has noticed that the roof puffs upward as the car moves. This is Bernoulli's principle again. Pressure outside against the top of the fabric, where air is moving, is less than the static atmospheric pressure inside the car. The result is an upward net force on the fabric. Atmospheric pressure beneath the paper pushes it upward, sweet and simple (Maitreya showed the same in the photo that opened this chapter).

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

Consider wind blowing across a peaked roof. The wind gains speed as it flows over the roof, as the crowding of streamlines in the sketch indicates. Pressure along the streamlines is reduced where they are closer together. The greater pressure inside the roof can lift it off the house. During a severe storm, the difference in outside and inside pressure doesn't need to be very much. A small pressure difference over a large area produces a force that can be formidable.

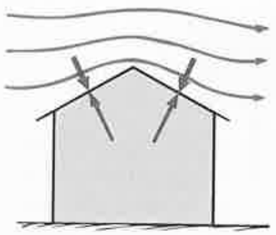

FIGURE 14.20

Air pressure above the roof is less than air pressure beneath the roof.

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

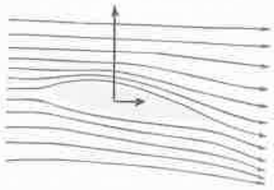

FIGURE 14.21

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

We all know that a baseball pitcher can impart a spin on a ball to make it curve off to one side as it approaches home plate. Similarly, a tennis player can hit a ball so it curves. A thin layer of air is dragged around the spinning ball by friction, which is enhanced by the baseball's threads or the tennis ball's fuzz. The moving layer of air produces a crowding of streamlines on one side. Note, in Figure 14.22b, that the streamlines are more crowded at B than at A for the direction of spin shown. Air pressure is greater at A, and the ball curves as shown.

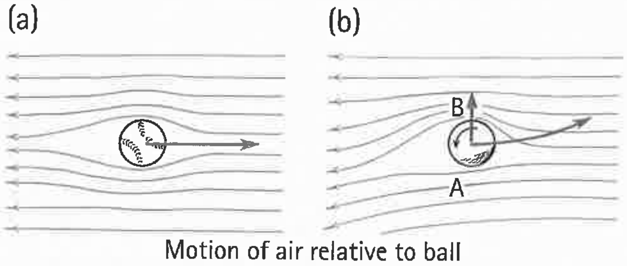

FIGURE 14.22

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

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

A familiar hand-operated sprayer, such as a perfume atomizer, utilizes Bernoulli's principle. When you squeeze the bulb, air rushes across the open end of a tube inserted into the perfume. This reduces the pressure in the tube, whereupon atmospheric pressure on the liquid below pushes it up into the tube, where it is carried away by the stream of air.

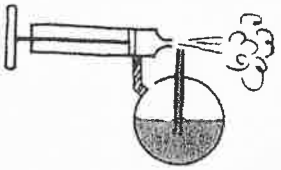

FIGURE 14.23

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

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

Practicing Physics

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

Bernoulli's principle explains why trucks passing closely on the highway are drawn to each other, and why passing ships run the risk of a sideways collision. Water flowing between the ships travels faster than water flowing past the outer sides. Streamlines are closer together between the ships than outside, so water pressure acting against the hulls is reduced between the ships. Unless the ships are steered to compensate for this, the greater pressure against the outer sides of the ships forces them together. Figure 14.24 shows how to demonstrate this in your kitchen sink or bathtub.

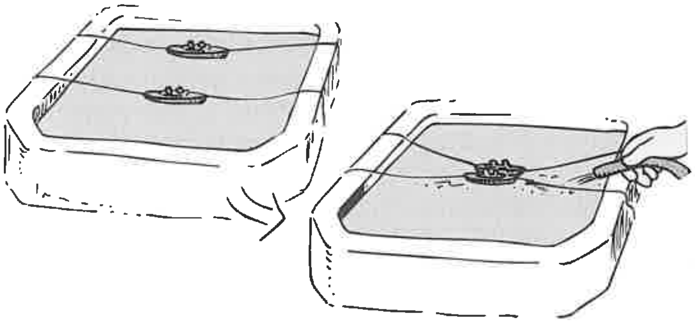

FIGURE 14.24
Loosely moor a pair of toy boats side by side in your sink. Then direct a stream of water between them. The boats will draw together and collide. Why?

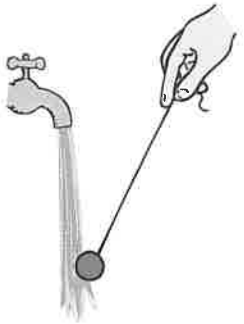

FIGURE 14.25
Pressure is greater in the stationary fluid (air) than in the moving fluid (water stream). The atmosphere pushes the ball into the region of reduced pressure.

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

FIGURE 14.26
The curved shape of an umbrella can be disadvantageous on a windy day.

CHECK POINT

A windy day makes for waves in a lake or the ocean. How does Bernoulli's principle help to explain the height of the waves?

Check Your Answer

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

Plasma

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

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

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

FIGURE 14.27

Streets are illuminated at night by glowing plasmas.

PLASMA IN THE EVERYDAY WORLD

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

Similarly, the neon gas in an advertising sign becomes a plasma when its atoms are ionized by electron bombardment. Neon atoms, after being activated by electric current, emit predominantly red light. The different colors seen in these signs correspond to plasmas made up of different kinds of atoms. Argon, for example, glows blue, and helium glows pink. Sodium vapor lamps used in street lighting emit yellow light stimulated by glowing plasmas (Figure 14.27).

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

FIGURE 14.28

In a plasma TV, hundreds of thousands of tiny pixels are lit up red, green, and/or blue by glowing plasmas. By combining these colors in different proportions, the entire color spectrum can be produced.

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

PLASMA POWER

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

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

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

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

SUMMARY OF TERMS

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

Barometer Any device that measures atmospheric pressure.

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

$$P_1V_1 = P_2V_2$$

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

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

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

REVIEW QUESTIONS

The Atmosphere

1. What is the energy source for the motion of gas in the atmosphere? What prevents atmospheric gases from flying off into space?
2. How high would you have to go in the atmosphere for half of the mass of air to be below you?

Atmospheric Pressure

3. What is the cause of atmospheric pressure?
4. What is the mass of a cubic meter of air at room temperature (20°C)?
5. What is the approximate mass of a column of air 1 cm^2 in area that extends from sea level to the upper atmosphere? What is the weight of this amount of air?
6. What is the pressure at the bottom of the column of air referred to in the previous question?

The Barometer

7. How does the pressure at the bottom of a 76-cm column of mercury in a barometer compare with air pressure at the bottom of the atmosphere?
8. How does the weight of mercury in a barometer compare with the weight of an equal cross section of air from sea level to the top of the atmosphere?
9. Why would a water barometer have to be 13.6 times taller than a mercury barometer?
10. When you drink liquid through a straw, is it more accurate to say the liquid is pushed up the straw rather than sucked up the straw? What exactly does the pushing? Defend your answer.
11. Why will a vacuum pump not operate for a well that is more than 10.3 m deep?
12. Why is it that an aneroid barometer is able to measure altitude as well as atmospheric pressure?

Boyle's Law

13. By how much does the density of air increase when it is compressed to half its volume?
14. What happens to the air pressure inside a balloon when it is squeezed to half its volume at constant temperature?
15. What is an ideal gas?

Buoyancy of Air

16. A balloon that weighs 1 N is suspended in air, drifting neither up nor down. (a) How much buoyant force acts on it? (b) What happens if the buoyant force decreases? (c) If it increases?
17. Does the air exert buoyant force on all objects in air or only on objects such as balloons that are very light for their size?

Bernoulli's Principle

18. What are streamlines? Is pressure greater or less in regions where streamlines are crowded?
19. What happens to the internal pressure in a fluid flowing in a horizontal pipe when its speed increases?
20. Does Bernoulli's principle refer to changes in internal pressure of a fluid or to pressures the fluid may exert on objects?

Applications of Bernoulli's Principle

21. How does Bernoulli's principle apply to the flight of airplanes?
22. Why does a spinning ball curve in its flight?
23. Why do ships passing close together run a risk of sideways collisions?

Plasma

24. How does a plasma differ from a gas?

Plasma in the Everyday World

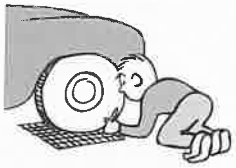
25. Cite at least three examples of plasma in your daily environment.

Plasma Power

26. What can be produced when a plasma beam is directed into a magnet?

PROJECTS

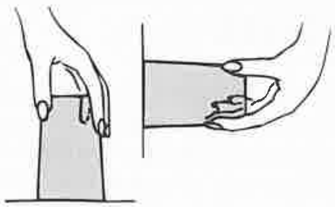
1. Compare the pressure exerted by the tires of your car on the road with the air pressure in the tires. For this project, you need the weight of your car, which you can get from a manual or a dealer. You divide the weight by 4 to get the approximate weight held up by one tire. You can closely approximate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



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

3. Hold a glass under water, allowing it to fill with water. Then turn it upside down and raise it, but with its mouth beneath the surface. Why does the water not flow out of the glass? How tall would a glass have to be before water began to flow out? (If you could find such a glass, you might need to cut holes in your ceiling and roof to make room for it!)

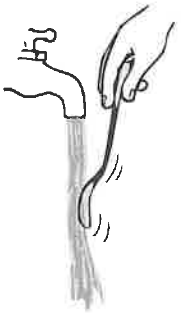
4. Place a card over the open top of a glass filled to the brim with water and invert it. Why does the card stay in place? Try it sideways.



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

8. Push a pin through a small card and place it in the hole of a thread spool. Try to blow the card from the spool by blowing through the hole. Try it in all directions.

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



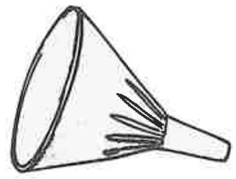
RANKING

1. Rank the volume of air in the glass, from greatest to least, when it is held
   a. near the surface as shown.
   b. 1 m beneath the surface.
   c. 2 m beneath the surface.
2. Rank the buoyant force supplied by the atmosphere on the following, from most to least:
   a. An elephant
   b. A helium-filled party balloon
   c. A skydiver at terminal velocity

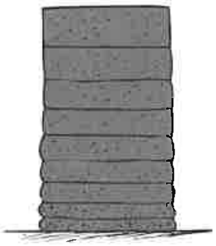
3. Rank from most to least, the amount of lift on the following airplane wings:
   a. Area 1000 m^2 with atmospheric pressure difference of 2.0 N/m^2
   b. Area 800 m^2 with atmospheric pressure difference of 2.4 N/m^2
   c. Area 600 m^2 with atmospheric pressure difference of 3.8 N/m^2

EXERCISES

1. It is said that a gas fills all the space available to it. Why, then, doesn't the atmosphere go off into space?
2. Why is there no atmosphere on the Moon?
3. Why is the pressure in an automobile's tires slightly greater after the car has been driven several kilometers?
4. If you count the tires on a large tractor-trailer that is unloading food at your local supermarket, you may be surprised to count 18 tires. Why so many tires? (*Hint:* Consider Project 1.)
5. The valve stem on a tire must exert a certain force on the air within to prevent any of that air from leaking out. If the diameter of the valve stem were doubled, by how much would the force exerted by the valve stem increase?
6. Why is a soft, underinflated football at sea level much firmer when it is taken to a high elevation in the mountains?
7. What is the purpose of the ridges that prevent the funnel from fitting tightly in the mouth of a bottle?
8. How does the density of air in a deep mine compare with the air density at Earth's surface?
9. When an air bubble rises in water, what happens to its mass, volume, and density?

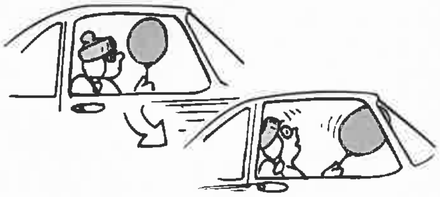


10. Two teams of eight horses each were unable to pull the Magdeburg hemispheres apart (shown at the top of the opening page of this chapter). Suppose that two teams of nine horses each could pull them apart. Then would one team of nine horses succeed if the other team were replaced with a strong tree? Defend your answer.
11. When boarding an airplane, you bring a bag of chips (or any other item packaged in an airtight foil package) and, while you are in flight, you notice that the bag puffs up. Explain why this happens.
12. Why do you suppose that airplane windows are smaller than bus windows?
13. We can understand how pressure in water depends on depth by considering a stack of bricks. The pressure below the bottom brick is determined by the weight of the entire stack. Halfway up the stack, the pressure is half because the weight of the bricks above is half. To explain atmospheric pressure, we should consider compressible bricks, like those made of foam rubber. Why is this so?

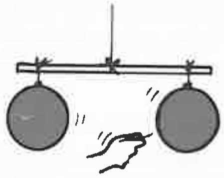


14. The "pump" in a vacuum cleaner is merely a high-speed fan. Would a vacuum cleaner pick up dust from a rug on the Moon? Explain.
15. Suppose that the pump shown in Figure 14.9 operated with a perfect vacuum. From how deep a well could water be pumped?

16. If a liquid only half as dense as mercury were used in a barometer, how high would its level be on a day of normal atmospheric pressure?
17. Why does the size of the cross-sectional area of a mercury barometer not affect the height of the enclosed mercury column?
18. From how deep a container could mercury be drawn with a siphon?
19. If you could somehow replace the mercury in a mercury barometer with a denser liquid, would the height of the liquid column be greater than or less than the height of the mercury? Why?
20. Would it be slightly more difficult to draw soda through a straw at sea level or on top of a very high mountain? Explain.
21. The pressure exerted against the ground by an elephant's weight distributed evenly over its four feet is less than 1 atmosphere. Why, then, would you be crushed beneath the foot of an elephant, while you're unharmed by the pressure of the atmosphere?
22. Your friend says that the buoyant force of the atmosphere on an elephant is significantly greater than the buoyant force of the atmosphere on a small helium-filled balloon. What do you say?
23. Which will register the greater weight: an empty flattened balloon or the same balloon filled with air? Defend your answer, then try it and see.
24. On a sensitive balance, weigh an empty, flat, thin plastic bag. Then weigh the bag filled with air. Will the readings differ? Explain.
25. Why is it so difficult to breathe when snorkeling at a depth of 1 m and practically impossible at a 2-m depth? Why can't a diver simply breathe through a hose that extends to the surface?
26. A little girl sits in a car at a traffic light holding a helium-filled balloon. The windows are closed and the car is relatively airtight. When the light turns green and the car accelerates forward, her head pitches backward but the balloon pitches forward. Explain why.



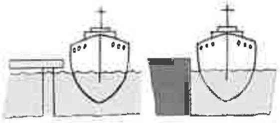
27. How does the concept of buoyancy complicate the old question "Which weighs more, a pound of lead or a pound of feathers"?
28. Why does the weight of an object in air differ from its weight in a vacuum (remembering that weight is the force exerted against a supporting surface)? Cite an example in which this would be an important consideration.
29. Would a bottle of helium gas weigh more or less than an identical bottle filled with air at the same pressure? Than an identical bottle with the air pumped out?
30. When you replace helium in a balloon with less-dense hydrogen, does the buoyant force on the balloon change if the balloon remains the same size? Explain.
31. A steel tank filled with helium gas doesn't rise in air, but a balloon containing the same helium rises easily. Why?
32. If the number of gas atoms in a container is doubled, the pressure of the gas doubles (assuming constant temperature and volume). Explain this pressure increase in terms of molecular motion of the gas.
33. What, if anything, happens to the volume of gas in an atmospheric research-type balloon when it is heated?
34. What, if anything, happens to the pressure of the gas in a rubber balloon when the balloon is squeezed smaller?
35. What happens to the size of the air bubbles released by a diver as they rise?
36. You and Tim float a long string of closely spaced helium-filled balloons over his used-car lot. You secure the two ends of the long string of balloons to different points on the ground so that the balloons float over the lot in an arc. What is the name of this arc? (Why could this exercise have been included in Chapter 12?)
37. The gas pressure inside an inflated rubber balloon is always greater than the air pressure outside. Explain.
38. Two identical balloons of the same volume are pumped up with air to more than atmospheric pressure and suspended on the ends of a stick that is horizontally balanced. One of the balloons is then punctured. Is the balance of the stick upset? If so, which way does it tip?



39. Two balloons that have the same weight and volume are filled with equal amounts of helium. One is rigid and the other is free to expand as the pressure outside decreases. When released, which will rise higher? Explain.
40. The force of the atmosphere at sea level against the outside of a 10-m^2 store window is about a million N. Why does this not shatter the window? Why might the window shatter in a strong wind blowing past the window?
41. Why does the fire in a fireplace burn more briskly on a windy day?
42. What happens to the pressure in water as it speeds up when it is ejected by the nozzle of a garden hose?
43. Why do airplanes normally take off facing the wind?
44. What provides the lift to keep a Frisbee in flight?
45. Imagine a huge space colony that consists of a rotating air-filled cylinder. How would the density of air at "ground level" compare to the air densities "above"?
46. Would a helium-filled balloon "rise" in the atmosphere of a rotating space habitat? Defend your answer.
47. When a steadily flowing gas flows from a larger-diameter pipe to a smaller-diameter pipe, what happens to (a) its speed, (b) its pressure, and (c) the spacing between its streamlines?
48. Compare the spacing of streamlines around a tossed baseball that doesn't spin in flight with the spacing of streamlines around one that does. Why does the spinning baseball veer from the course of a nonspinning one?
49. Why is it easier to throw a curve with a tennis ball than a baseball?
50. Why do airplanes extend wing flaps that increase the area and the angle of attack of the wing during takeoffs and

landings? Why are these flaps pulled in when the airplane has reached cruising speed?

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



56. Is lower pressure the result of fast-moving air, or is fast-moving air the result of lower pressure? Give one example supporting each point of view. (In physics, when two things are related—such as force and acceleration or speed and pressure—it is usually arbitrary which one we call *cause* and which one we call *effect*.)

PROBLEMS

1. What change in pressure occurs in a party balloon that is squeezed to one-third its volume with no change in temperature?
2. Estimate the buoyant force that air exerts on you. (To do this, you can estimate your volume by knowing your weight and by assuming that your weight density is a bit less than that of water.)
3. A mountain-climber friend with a mass of 80 kg ponders the idea of attaching a helium-filled balloon to himself to effectively reduce his weight by 25% when he climbs. He wonders what the approximate size of such a balloon would be. Hearing of your physics skills, he asks you. Share with him your calculations that show the volume of the balloon to be about 17 m^3 (slightly more than 3 m in diameter for a spherical balloon).
4. On a perfect fall day, you are hovering at low altitude in a hot-air balloon, accelerated neither upward nor downward. The total weight of the balloon, including its load and the hot air in it, is 20,000 N.
   a. Show that the weight of the displaced air is 20,000 N.
   b. Show that the volume of the displaced air is 1700 m^3.
5. Consider an airplane with a total wing surface of 100^2 m. At a certain speed the difference in air pressure below and above the wings is 4% of atmospheric pressure. Show that the lift on the airplane is 400,000 N.
- **6.** The weight of the atmosphere above 1 m^2 of Earth's surface is about 100,000 N. Density, of course, becomes less with altitude. But suppose the density of air were a constant 1.2 kg/m^3. Calculate where the top of the atmosphere would be.

CHAPTER 14 ONLINE RESOURCES

PhysicsPlace.com™

Videos

- Air Has Weight
- Air Is Matter
- Air Has Pressure
- Buoyancy of Air

Quizzes

Flashcards

Links

PART TWO MULTIPLE-CHOICE PRACTICE EXAM

Choose the best answer to the following:

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

After you have made thoughtful choices, and discussed them with your friends, find the answers on page 681.