# Chapter 3

# ENERGY: A CLOSER LOOK

Chapter 1 began by distinguishing matter and energy, and I defined energy as "the stuff that makes everything happen." That's not a very scientific definition, but it captures the essence of what energy is. You probably have your own intuitive sense of energy, which you reveal when you speak of a "high-energy" person or performance, when you find an event "energizing," or when, at the end of a long day, you're "low on energy." In all these cases, *energy* seems to be associated with motion, activity, or change—hence, energy as "the stuff that makes everything happen." In this chapter, I'll gradually lead you to a more scientific understanding of energy.

The distinction between matter and energy is a convenience in describing our everyday world, but fundamentally the two are manifestations of a single, basic "stuff" that makes up the universe. As Einstein showed with his famous equation $E = mc^2$, energy and matter are interchangeable. The equation shows that matter with mass $m$ can be converted to energy $E$ in the amount $mc^2$, where $c$ is the speed of light. You can turn matter into energy, and vice versa, but the total amount of "stuff"—call it *mass–energy* for want of a better term—doesn't change. In our everyday world, however, the interchange of matter and energy is a very subtle effect, essentially immeasurable. So for us it's convenient to talk separately of matter and energy, and to consider that each is separately conserved. That's the approach I'll take almost everywhere in this book.

Energy can change from one form to another. For example, a car's engine converts some of the energy stored in gasoline into the energy of the car's motion, and ordinary friction brakes turn that energy into heat as the car slows. But energy can't disappear into nothingness, nor can it be created. In addition to changing form, energy can also move from one place to another. For example, a house cools as thermal energy inside the house flows out through the walls. But again the energy isn't gone; it's just relocated.

Although this treatment of energy and matter as distinct and separately conserved substances is justified in our everyday world, you should be aware that there are times and places where the interchange of matter and energy is so blatantly obvious that it can't be ignored. During the first second of the universe's existence, following the Big Bang, the average energy level was so high that matter particles could form out of pure energy, and matter could annihilate with antimatter to form pure energy. Neither energy nor matter was separately conserved. I'll have more to say about the interchangeability of matter and energy when we explore nuclear energy in Chapter 7.

## 3.1 Forms of Energy

Stand by the roadside as a truck roars by, and you have a gut sense of the vast energy associated with its motion. This energy of motion, **kinetic energy**, is perhaps the most obvious form of energy. But here's another, more subtle form: Imagine climbing a rock cliff, a process you can feel takes a lot of energy. You also know the danger you face, a danger that exists because the energy you put into the climb isn't gone, but could reappear as kinetic energy were you to fall. Or imagine that I lift a bowling ball and hold it over your head; again you're aware of a danger from an energy that isn't visibly obvious but that you know could reappear as kinetic energy of the ball's downward motion. This energy, associated with an object that's been lifted against Earth's gravity, is **potential energy**; specifically, **gravitational potential energy**. It's potential because it has the potential to turn into the more obvious kinetic energy, or for that matter into some other form. Stretch a rubber band or bungee cord, draw a bow or a slingshot, or compress a spring, and again you sense that there's stored energy. This is called **elastic potential energy** because it involves changing the configuration of an elastic substance. Figure 3.1 shows simple examples of potential and kinetic energy.

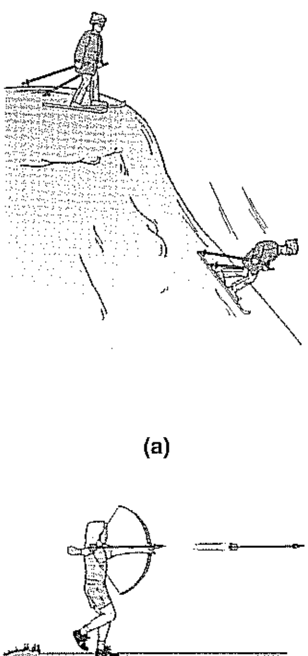

(a)
(b)

**FIGURE 3.1**
Potential and kinetic energy. (a) Gravitational potential energy of the skier becomes kinetic energy as she heads down the slope. (b) Elastic potential energy stored in the bow becomes kinetic energy of the arrow.

### FORCE AND ENERGY

Are there other forms of energy? In the context of this book and its emphasis on the energy that powers human society, you might think of answers such as "coal," "wind energy," "solar energy," "waterpower," and the like. But here we'll take a more fundamental look at the different types of energy available to us. There's the kinetic energy associated with moving objects—essentially the same type of energy whether those objects are subatomic particles, trucks on a highway, Earth orbiting the Sun, or our whole Solar System in its stately 250-million-year circle around the center of the Milky Way galaxy. Then there's potential energy, which is intimately related to another fundamental concept—that of **force**. At the everyday level, you can think of a force as a push or a pull. Some forces are obvious, such as the pull of your arm as you drag your luggage through the airport, or the force your foot exerts when you kick a soccer ball. Others are equally evident but less visible, such as the gravitational force that pulls an apple from a tree or holds the Moon in its orbit, the force of attraction between a magnet and a nail, or the frictional force that makes it hard to push a heavy piece of furniture across the floor.

Today, physicists recognize just three fundamental forces that appear to govern all interactions in the universe. For our purposes I'm going to discuss the **gravitational force**, the **electromagnetic force**, and the **nuclear force**, although a physicist would be quick to point out that the electromagnetic and nuclear forces are instances of more fundamental forces. You'll sometimes see the *weak force* mentioned as well. It's important in some nuclear reactions we'll see in Chapter 7, but physicists now understand it as a close cousin of the electromagnetic force. The "holy grail" of science is to understand all these forces as aspects of a single interaction that governs all matter and energy, but we're probably some decades away from achieving that understanding. Figure 3.2 suggests realms and applications in which each of the fundamental forces is important.

Gravity seems familiar, since we're acutely aware of it in our everyday lives here on Earth. Earth has no monopoly on gravity; it's the Sun's gravity that tugs on Earth to keep our planet on its yearlong orbital journey. Actually, gravity is universal; it's a force of attraction that acts between every two pieces of matter in the universe. But it's the weakest of the fundamental forces and is significant only with large-scale accumulations of matter such as planets and stars.

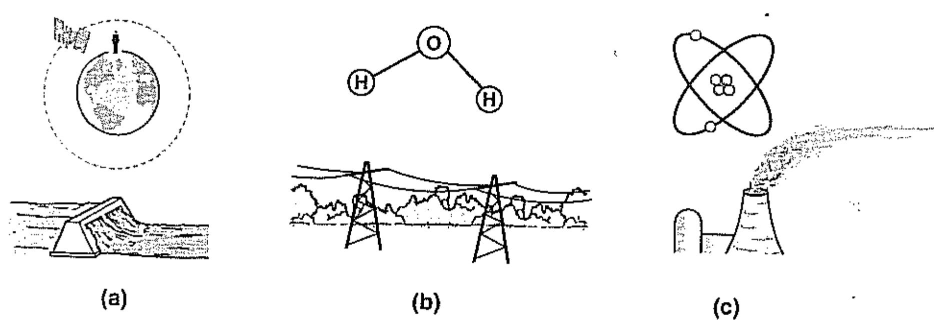



**FIGURE 3.2**

The fundamental forces and some applications relevant to this book. (a) Gravity governs the large-scale structure of the universe. It holds you to Earth and keeps a satellite in orbit. Gravitational potential energy is the energy source for hydroelectric power plants. (b) The electromagnetic force is responsible for the structure of matter at the molecular level; the associated potential energy is released in chemical reactions such as those that occur in burning fuels. Electromagnetism is also involved in the production and transmission of electrical energy. (c) The nuclear force binds protons and neutrons to make atomic nuclei. The associated potential energy is the energy source for nuclear power plants.

The electromagnetic force comprises two related forces involving electricity and magnetism. The electric force acts between matter particles carrying the fundamental property we call electric charge. It's what binds atoms and molecules, and is involved in chemical reactions. The magnetic force also acts between electric charges, but only when they're in relative motion. In this sense magnetism is intimately related to electricity. The two are complementary aspects of the same underlying phenomenon, which we call electromagnetism. That complementarity has much to do with the ways we generate and transmit electrical energy; thus electromagnetism is vitally important to our energy technologies.

The nuclear force binds together the protons and neutrons that form atomic nuclei. It's the strongest of the three forces—a fact that accounts for the huge difference between nuclear and chemical energy sources, as I'll describe in Chapter 7. We can thank nuclear forces acting deep inside the Sun for the stream of sunlight that supplies nearly all the energy arriving at Earth.

Forces can act on matter to give it kinetic energy, as when an apple falls from a tree and the gravitational force increases its speed and hence its kinetic energy, or when, under the influence of the electric force, an electron "falls" toward a proton to form a hydrogen atom and the energy ultimately emerges as a burst of light. Alternatively, when matter moves against the push of a given force, energy is stored as potential energy. That's what happened when I lifted that bowling ball over your head a few paragraphs ago, or when you pull two magnets apart, or when you (or some microscopic process) yank that electron off the atom, separating positive and negative charge by pulling against the attractive electric force. So each of the fundamental forces has associated with it a kind of potential energy.

What happened to all those other kinds of forces, like the push of your hand or the kick of your foot, or the force in a stretched rubber band, or friction? They're all manifestations of one of the three fundamental forces. And in our everyday lives, the only forces we usually deal with are gravity and the electromagnetic force. Gravity is pretty obvious: We store gravitational energy any time we lift something or climb a flight of stairs. We gain kinetic energy from gravity when we drop an object, take a fall, or coast down a hill on a bicycle or skis. We exploit the gravitational force and gravitational energy when we generate electricity from falling water. All the other forces we deal with in everyday life are ultimately electromagnetic, including the forces in springs, bungee cords, and rubber bands, and the associated potential energy. More significantly for our study of human energy use, the energy stored in the food we eat and in the fuels we burn is fundamentally electromagnetic energy. The energy stored in a molecule of gasoline, for example, is associated with arrangements of electric charge that result in electromagnetic potential energy. (In these cases the energy is essentially all electrical energy; magnetism plays no significant role in the interactions among atoms that are at the basis of chemistry and chemical fuels.) In this book, we're also concerned with one form of energy that isn't either gravitational or electromagnetic—namely, the nuclear energy that we use to generate electricity and that our star uses to make sunlight.

## 3.2 Electrical Energy: A Closer Look

You probably know that electricity, as we commonly think of it, is a flow of electrons through a wire. That flow is called **electric current**, and what's important here is that the electrons carry **electric charge**, a fundamental electrical property of matter. Electrons carry negative charge, and protons carry equal but opposite positive charge. Because electrons are much lighter, they're usually the particles that move to carry electric current. You might think that the energy associated with electricity is the kinetic energy of those moving electrons, but this isn't the case. The energy associated with electricity, and with its close cousin, magnetism, is in the form of invisible **electric fields** and **magnetic fields** created by the electric charges of the electrons and protons that make up matter. In the case of electric current, electric and magnetic fields surround a current-carrying wire and act together to move electrical and magnetic energy along the wire. Although a little of that moving energy is inside the wire, most is actually in the space immediately around it! Although we call it *electrical* energy, the energy associated with electric current actually involves magnetism as well as electricity, so strictly speaking it's *electromagnetic* energy. However, I'll generally stick with common usage and call it *electrical energy* or just *electricity*.

### MAKING ELECTRICITY

Electricity is an important and growing form of energy in modern society. In the United States, for example, about 40% of our overall energy consumption goes toward making electricity, although only about a third of that actually ends up as electricity, for important reasons that I'll discuss in the next chapter. Electrical energy plays an increasingly important role for two reasons. First, it's versatile: Electrical energy can be converted with nearly 100% efficiency to any other kind of energy—mechanical energy, heat, light, or whatever you want. Second, electrical energy is especially easy to transport. Thin wires made from electrically conducting material are all it takes to guide the flows of electrical energy over hundreds and even thousands of miles.

How do we produce electrical energy? In principle, any process that forces electric charges apart will do the trick. In **batteries**, chemical reactions separate positive and negative charge, transforming the energy contained within individual molecules into the energy associated with distinct regions of positive and negative charge—the two terminals of the battery (Fig. 3.3). Hook a complete circuit between the terminals, such as a lightbulb, motor, or other electric device, and current flows through it, converting electrical energy into light, mechanical energy, or whatever.

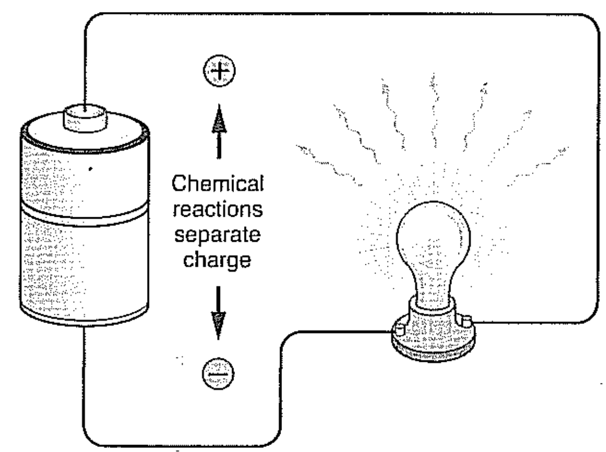


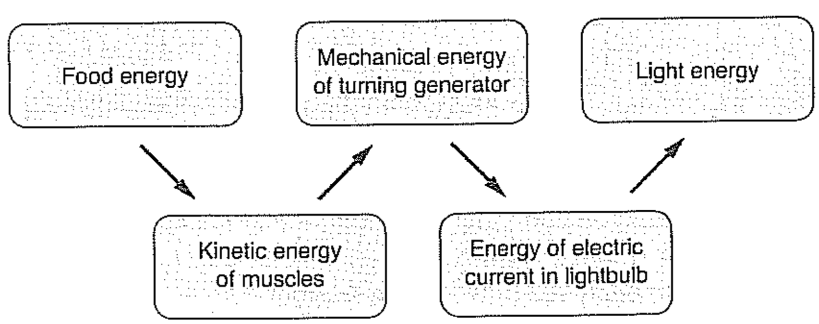

**FIGURE 3.3**
Chemical reactions in a battery separate positive and negative charge. Connecting an external circuit, such as the lightbulb shown here, allows the battery to deliver electrical energy as charge flows through the circuit.

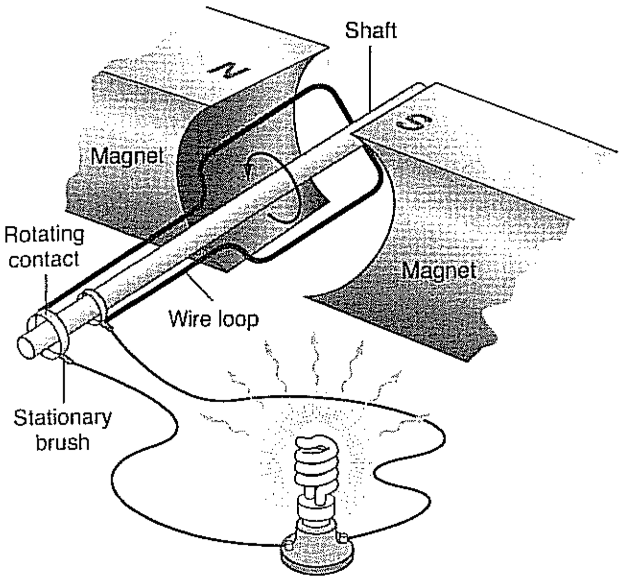
In some batteries, the chemical reactions go only one way, and when the chemicals have given up all their energy, the battery is "dead" and must be discarded (or, better, recycled). In other batteries, the chemical reactions can be reversed by forcing electric current through the battery in the direction opposite its normal flow. In this mode, electrical energy is converted into chemical energy, which is the opposite of what happens in the battery's normal operation. Such batteries are, obviously, **rechargeable**. Rechargeable batteries power your cell phone, laptop, and cordless tools, and it's a large rechargeable battery that starts your car or, if you have a gas-electric hybrid, provides some of the car's motive power. Batteries are great for portable devices, but they're hardly up to the task of supplying the vast amounts of electrical energy that we use in modern society. Nor are most batteries available today a serious alternative to gasoline and diesel fuel as sources of energy for transportation, although advances in battery technology are closing that gap.

A cousin of the battery is the **fuel cell**, which, conceptually, is like a battery whose energy-containing chemicals are supplied continually from an external source. Today fuel cells find use in a number of specialized applications, including on spacecraft and as backup sources of electrical energy in the event of power failures. Fuel cells show considerable promise for transportation, although issues of cost and fuel storage currently limit that use.

So where does most of our electrical energy come from, if not from batteries? It originates in a phenomenon that reflects the intimate connection between electricity and magnetism. Known since the early nineteenth century and termed **electromagnetic induction**, this fundamental phenomenon entails the creation of electrical effects from *changing* magnetism. Wave a magnet around in the vicinity of a loop of conducting wire, and an electric current flows in the wire. Move a magnetized strip past a wire coil and you create a current in the coil, which is what happens when you swipe your credit card to pay for your groceries. And on a much larger scale, rotate a coil of wire in the vicinity of a magnet and you have an electric generator that can produce hundreds of millions of watts of electric power. It's from such generators that the world gets the vast majority of its electricity (Fig. 3.4).

Remember, however, that energy is conserved, so an electric generator can't actually *make* energy; rather, it converts mechanical energy into electrical energy. Recall Figure 2.1, which shows a person turning a hand-cranked electric generator to power a lightbulb. The person turning the generator is working hard because the electrical energy to light the bulb comes from her muscles. The whole sequence goes something like this:



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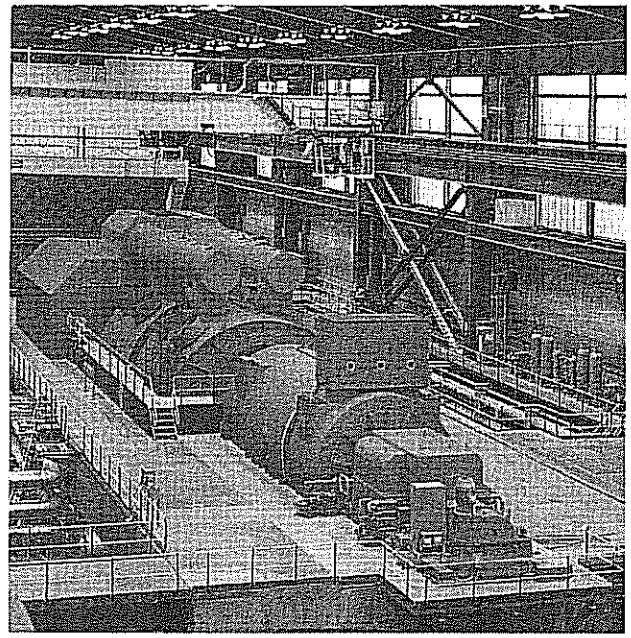

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**FIGURE 3.4**
(a) A simple electric generator consists of a single wire loop rotating between the poles of a magnet. The stationary brushes allow current to flow from the rotating contacts to the external circuit. A practical generator has many loops, each with many turns of wire. (b) This large generator at an electric power plant produces 650 MW of electric power.

Had the lightbulb been off, and not connected in a complete circuit to the generator, the generator would have been very easy to turn. Why? Because turning it wouldn't produce electrical energy, so the turner wouldn't need to supply any energy. So how does the generator "know" to become hard to turn if the lightbulb is connected? Ultimately, the answer lies in another fundamental relationship between electricity and magnetism: Electric current—*moving* electric charge—is what gives rise to magnetism; that's how an electromagnet works. So when current is flowing, there are *two* magnets in the generator—the original, "real" magnet that was built into the generator, and the electromagnet arising from current flowing through the rotating coil. These two magnets repel each other, and that's what makes the generator hard to turn.

I'm going into this level of physics detail because I want you to be acutely aware of what happens every time you turn on a lightbulb, a stereo, a TV, a hair dryer, or an electric appliance: More current flows, and somewhere an electric generator gets harder to turn. Despite my fanciful energy servants of Chapter 2, the generators that produce our electric power aren't cranked by human hands. Most are turned by high-pressure steam created using heat from the combustion of fossil fuels or the fissioning of uranium, while some are turned by flowing water, geothermal steam, or wind (Fig. 3.5). So when you turn on that light or whatever, a little more fossil fuel has to be burned, or uranium fissioned, or water let through a dam, to satisfy your demand for energy. The electric switches you choose to flip on are one of your direct connections to the energy-consumption patterns described in Chapter 2, and the physical realization of that connection is in the electromagnetic interactions that make electric generators hard to turn.

There are a handful of other approaches to separating electric charge and thus generating electrical energy, but only one holds serious promise for large-scale

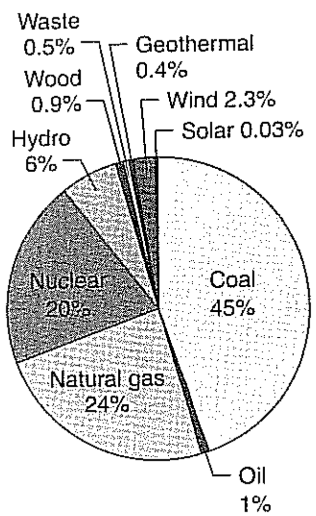


**FIGURE 3.5**
Sources of electrical energy in the United States.

electric energy production. This is the technology of **photovoltaic cells**, semiconductor devices in which the energy of sunlight separates charge and drives electric current. Photovoltaic technology has long been used for remote applications, ranging from spacecraft to weather stations to traffic signals to pumping water in villages of the developing world. As Figure 3.5 shows, solar energy today generates a mere 0.03% of U.S. electricity. But solar energy's contribution is increasing rapidly, largely through advances in the technology and economics of photovoltaic cells. You'll learn more about photovoltaics in Chapter 9.

## STORED ELECTRICAL ENERGY

Electrical energy is associated not only with electric currents and the batteries, generators, and photovoltaic devices that drive them; it also exists in every configuration of electric charges. Since matter is made up of electrons and protons, all matter contains electrical energy. Just how much depends on how the electric charges are arranged. We can create stored electrical energy, for example, by putting positive charge on one metal surface and negative charge on a separate, nearby metal surface. Configurations such as this one store the energy that powers a camera flash or represents information saved in your computer's memory. A larger but similar example is a lightning storm, in which electrical energy is stored in the electric fields associated with layers of charge that build up in violent storm clouds. That energy is released—converted to heat, light, and sound—by lightning discharges. In these and the cases I'll describe next, by the way, the term *electrical energy* is more appropriate than *electromagnetic energy*; magnetism plays a very small role in the energy storage associated with configurations of electric charge, especially when the movement of charge is not significant.

Far more important than the energy of a lightning storm or energy-storage technology is the electrical energy stored at the microscopic level in the configurations of electric charge that we call molecules. Molecules, made up of anywhere from a few to a few thousand atoms, are arrangements of the electric charges that make up their constituent atoms. How much energy is stored in a given molecule depends on its physical structure, which changes in the chemical reactions that rearrange atoms. Most fuels, including in particular the fossil fuels that I introduced in Chapter 1, are substances that store energy in the electric fields associated with their molecular arrangements of electric charges. Gasoline, for example, has molecules consisting of carbon and hydrogen. When gasoline burns, its molecules interact with atmospheric oxygen to form carbon dioxide ($CO_2$) and water ($H_2O$). The total electrical energy stored in the $CO_2$ and $H_2O$ molecules is less than what was in the original gasoline and oxygen, so the process of burning gasoline releases energy.

So fossil fuels store energy, ultimately, as electrical energy of molecular configurations. We generally call that stored energy **chemical energy**, because chemistry is all about the interaction of atoms to make molecules. But the origin of chemical energy is in the electrical nature of matter. By the way, not all fuels are chemical. In Chapter 1, I mentioned the nuclear fuels that power our reactors and bombs; they derive their energy from fields associated with electrical and nuclear forces that act among particles within the atomic nucleus. I'll continue to use the term *fuel* broadly to mean a substance that stores energy in its microscopic structure, at either the atomic/molecular level (chemical fuel) or at the nuclear level (nuclear fuel).

Magnetism is intimately related to electricity and it, too, can store energy. Magnetic energy plays a lesser role than electricity in our everyday lives, although it is associated with the conversion of mechanical energy to electrical energy in electric generators, and vice versa in electric motors. Magnetic energy storage is important in some technological devices, and it plays a major role in the giant eruptive outbursts that occur on our Sun and sometimes hurl high-energy particles toward Earth. The brilliant auroral displays visible at high latitudes are the result of these particles interacting with Earth's own magnetic field and atmosphere. Although stored magnetic energy is of less practical importance than stored electrical energy, be aware that any flow or movement of what you might want to call electrical energy must necessarily involve magnetism, too. This is the case for the current-carrying wire that I discussed at the beginning of this section (Section 3.2), and it's especially true of another means of energy transport that I'll describe next.

## ELECTROMAGNETIC RADIATION

The Sun is the ultimate source of the energy that powers life on Earth. As shown in Figure 1.8, our star accounts for 99.98% of the energy reaching Earth's surface. We'll see in Chapter 7 how the Sun's energy arises from nuclear reactions deep in the solar core, but here's the important point for now: Sunlight carries energy across the 93 million miles of empty space between Sun and Earth, so light itself must be a form of energy. Light—along with radio, microwaves, infrared, ultraviolet, X rays, and the penetrating nuclear radiation known as gamma rays—is a kind of energy-in-transit called **electromagnetic radiation**. Light and other electromagnetic radiation are made up of **electromagnetic waves**, structures of electric and magnetic fields in which change in one field regenerates the other to keep the wave moving and carrying energy through empty space (Figures 3.6 and 3.7). I'll occasionally talk of "light energy" or

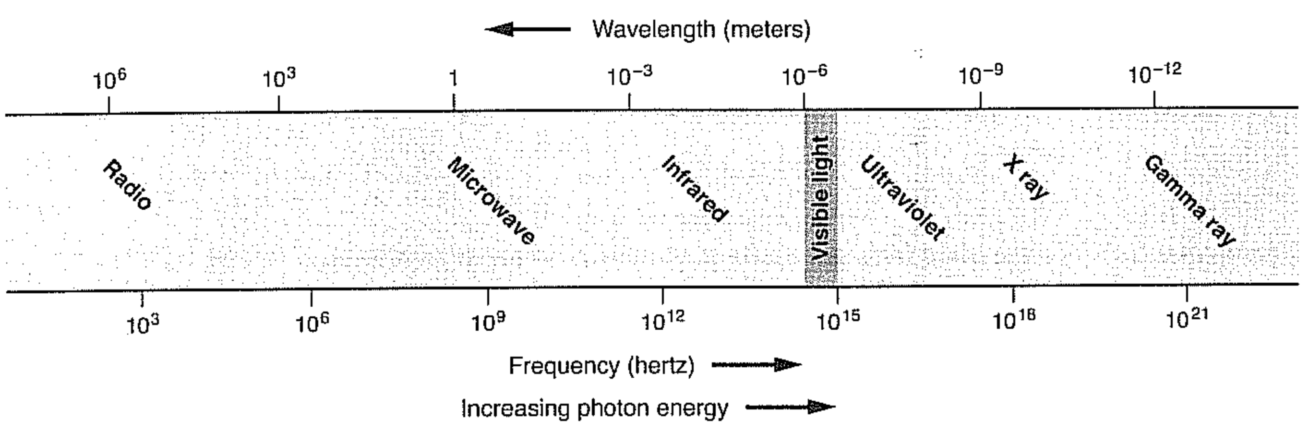


**FIGURE 3.6**
The electromagnetic spectrum. Electromagnetic waves are characterized by their frequency in hertz (wave cycles per second) or their wavelength in meters (the distance between wave crests). The two are inversely related. Note the nonlinear scale, with each tick mark representing a factor of 1,000 increase or decrease in frequency or wavelength. The Sun's energy output is mostly in the visible and adjacent infrared portion of the spectrum, with a little ultraviolet.

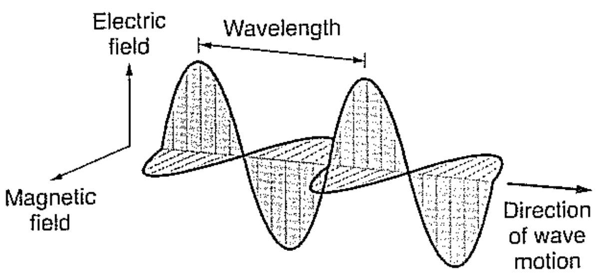


**FIGURE 3.7**
Structure of an electromagnetic wave. The wave carries energy in its electric and magnetic fields, which are at right angles to each other and to the direction in which the wave is traveling.

"the energy of electromagnetic radiation" as though these were yet another form of energy, but ultimately, light and other electromagnetic radiation are a manifestation of the energy contained in electric and magnetic fields.

Electromagnetic waves originate in the accelerated motion of electric charges—electric currents in antennas producing radio waves; the jostling of charges in a hot object, causing it to glow; atomic electrons jumping between energy levels to produce light; atomic nuclei rearranging themselves and emitting gamma rays. And when electromagnetic waves interact with matter, it's ultimately through their fields producing forces on electric charges—a TV signal moving electrons in an antenna; light exciting nerve impulses in the receptor cells of your eye; sunlight jostling electrons in a solar collector to produce heat, or in the chlorophyll of a green plant to produce energy-storing sugar.

Although it usually suffices to think of electromagnetic radiation in terms of waves, at the subatomic level the interaction of radiation with matter involves quantum physics. Specifically, the energy in electromagnetic waves comes in "bundles" called **photons**, and it's the interaction of individual photons with electrons that transfers electromagnetic wave energy to matter. For a given frequency $f$ of electromagnetic wave, there's a minimum possible amount of energy, corresponding to one photon. That photon energy is directly proportional to the frequency $f$: $E = hf$, where proportionality constant $h$ is **Planck's constant.** In SI units, $h = 6.63 \times 10^{-34}$ J·s, and it's a measure of *quantization*—the existence of discrete values for many physical quantities at the atomic and subatomic level. For any wave, the product of frequency $f$ and wavelength $\lambda$ is the wave speed. For electromagnetic waves, that's the speed of light, $c$ ($3.00 \times 10^{8}$ m/s). Therefore we can write the photon energy in terms of either frequency or wavelength:

$$E = hf = \frac{hc}{\lambda} \qquad \text{(photon energy)} \qquad (3.1)$$

We'll find the concept of quantized energy and photons especially useful in Chapter 9's description of photovoltaic solar energy conversion.

## 3.3 Quantifying Energy

A common argument against increased use of solar energy is that there isn't enough of it. That argument is wrong, as I'll make clear in Chapter 9, but you can't very well rebut it unless you have a quantitative answer to the question "How much is there?" You may be enthusiastic about wind energy, but unless you can convince me that the wind resource is sufficient in quantity for wind to make a significant contribution to our energy needs, I'm unlikely to share your enthusiasm. A noted environmentalist claims that buying an SUV instead of a regular car wastes as much energy as leaving your refrigerator door open for

7 years. Is this right? Or is it nonsense? You can't make a judgment unless you can get quantitative about energy.

As these examples suggest, we often need to use numerical quantities to describe amounts of energy and rates of energy use. In Chapter 2, I introduced a basic unit of power, or rate of energy use—the watt (W). I explained what a watt is by quantifying the rate at which your own body can produce energy, about 100 W. I also introduced the prefix *kilo*, meaning 1,000, hence the kilowatt (kW, or 1,000 W). I emphasized the distinction between power—the rate of energy use—and actual amounts of energy. And I introduced one unit that's often used to describe amounts of energy, namely the kilowatt-hour (kWh). Again, here's the relationship between power and energy: Power is a rate and can be expressed in energy units per time units. Equivalently, energy amounts can be expressed in power units multiplied by time units; hence the kilowatt-hour as an energy unit.

Suppose you use energy at the rate of 1 kW for 2 hours. Then you've used (1 kW) × (2 h) = 2 kWh of energy. Or suppose you consume 60 kWh of energy in 2 hours. Then your energy-consumption rate is (60 kWh)/(2 h) = 30 kW. Notice how the units work out in this second calculation: The hours (h) cancel, giving, correctly, a unit of power, in this case the kilowatt. Even simpler: If you use 1 kWh of energy in 1 hour, your rate of energy consumption is 1 kWh/h, or just 1 kW. That is, a kilowatt-hour per hour is exactly the same as a kilowatt.

## ENERGY UNITS

Still, the kilowatt-hour, although a perfectly good energy unit, seems a bit cumbersome. Is there a simple unit for energy itself that isn't expressed as a product of power with time? There are, in fact, many. In the International System of Units (SI, as it's abbreviated from the French *Système international d'unités*), the official energy unit is the **joule** (J), named for the British physicist and brewer James Joule (1818–1889), who explored and quantified the relationship between mechanical energy and heat. SI is the standard unit system for the scientific community (and for most of the everyday world beyond the United States). If this were a pure science text, I would probably insist on expressing all energies in joules from now on. But energy is a subject of interest to scientists, economists, policymakers, investors, engineers, nutritionists, corporate executives, athletes, and many others, and as a result there are a great many different energy units in common use. I'll describe a number of them here, but I'll generally limit most of the discussion in this book to the joule, the kilowatt-hour, and only occasionally other units.

So what's a joule? In the spirit of your muscle-based understanding of the watt, consider that this book weighs around 2 pounds. Lift it about 4 inches and you've expended about 1 J of energy, which is now stored as gravitational potential energy. In Section 3.4 I'll explain how I did this calculation, and I'll use a similar calculation to verify the 100-W figure from the knee-bend exercise in Chapter 2.

More formally, a joule is a watt-second: 1 J = 1 W·s. That is, if you use energy at the rate of 1 W for 1 second, then you've used 1 J of energy. Use energy at the rate of 1 kW for 1 second, and you've used (1,000 W) × (1 s) = 1,000 W·s = 1,000 J, or 1 kilojoule (kJ). Use energy at the rate of 1 kW for a full hour—3,600 seconds—and you've used (1,000 W) × (3,600 s) = 3.6 million W·s, or 3.6 megajoules (MJ; here the prefix *mega* stands for million). But 1 kW for 1 hour amounts to 1 kWh, so 1 kWh is 3.6 MJ.

The joule is the official energy unit of the scientific community, but there are plenty of others. Table 3.1 lists a number of them, along with their equivalents in joules. A unit often used in biology, chemistry, and nutrition is the **calorie** (cal). One calorie is defined as the amount of energy it takes to raise the temperature of 1 gram of water by 1 degree Celsius (°C). The calorie was named before the connection between energy and heat was understood (more on this in Chapter 4). It was Joule himself who established this connection; today, we know that 1 cal is 4.184 J. (There are actually several definitions for the calorie, which vary slightly. I'm using what's called the *thermochemical calorie*.) You're probably most familiar with the calorie as something to be conscious of if you don't want to gain weight. The caloric value of food is indeed a measure of the food's energy content, but since your body stores unused food energy as chemical energy in molecules of fat, it's also an indication of potential weight gain. The "calorie" you see listed on a food's nutritional label is actually 1,000 cal, correctly called a *kilocalorie* (kcal) or sometimes *food calorie* or *large calorie* and written with a capital C: Calorie. Obviously, 1 kcal is then 4,184 J or 4.184 kJ. By the way, "low-calorie soda" might be a meaningful description for an American, but in other countries it's "low-joule soda," making obvious the point that calories and joules measure the same thing—namely, energy (Fig. 3.8).

Since the calorie is a unit of energy, calories per time is a unit of power, convertible to watts. I'll let you show (in Exercise 1 at the end of this chapter) that the average human diet of 2,000 kcal per day is roughly equivalent to 100 W, thus providing another confirmation of Chapter 2's value of 100 W for the typical power output of the human body.


**FIGURE 3.8**
"Low joule" describes this diet soft drink from Australia. Joules and calories measure the same thing, namely energy.

In the English system of units, no longer used in England but only in the United States and a very few other countries, the analog of the calorie is the **British thermal unit** (Btu), defined as the amount of energy needed to raise the temperature of 1 pound of water by 1 degree Fahrenheit (°F). Table 3.1 shows that 1 Btu is 1,054 J, or just over 1 kJ. You could also calculate this conversion knowing the relationship between grams and pounds, and the Celsius and Fahrenheit scales (see Exercise 2). A power unit often used in the United States to describe the capacity of heating and air conditioning systems is the Btu per hour (Btu/h, but often written, misleadingly, as simply Btuh). As Table 3.1 shows, 1 Btu/h is just under one-third of a watt. My household furnace is rated at 112,000 Btu/h; Example 3.1 shows that this number is consistent with its fuel consumption rate of about 1 gallon of oil per hour. The British thermal unit is at the basis of a unit widely used in describing energy consumption of entire countries, namely the **quad** (Q). One quad is 1 quadrillion Btu, or $10^{15}$ Btu. The world's rate of energy consumption in the early twenty-first century is nearly 500 Q per year, with the United States and China each accounting for about 100 Q annually.

## TABLE 3.1 | ENERGY AND POWER UNITS

| Energy units | Joule equivalent* | Description |
|---|---|---|
| joule (J) | 1 J | Official energy unit of the SI unit system; equivalent to 1 W·s or the energy involved in applying a force of 1 newton over a distance of 1 meter. |
| kilowatt-hour (kWh) | 3.6 MJ | Energy associated with 1 kW used for one hour. (1 MJ = $10^6$ J) |
| gigawatt-year | 3.16 PJ | Energy produced by a typical large (1 gigawatt) power plant operating full-time for one year. (1 PJ = $10^{15}$ J) |
| calorie (cal) | 4.184 J | Energy needed to raise the temperature of 1 gram of water by 1°C. |
| British thermal unit (Btu) | 1,054 J | Energy needed to raise the temperature of 1 pound of water by 1°F, very roughly equal to 1 kJ. |
| quad (Q) | 1.054 EJ | Quad stands for quadrillion Btu, or $10^{15}$ Btu, and is roughly equal to 1 exajoule ($10^{18}$ J). |
| erg | $10^{-7}$ J | Energy unit in the centimeter-gram-second system of units. |
| electron volt (eV) | $1.6 \times 10^{-19}$ J | Energy gained by an electron dropping through an electric potential difference of 1 volt; used in atomic and nuclear physics. |
| foot-pound | 1.356 J | Energy unit in the English system, equal to the energy involved in applying a force of 1 pound over a distance of 1 foot. |
| tonne oil equivalent (toe) | 41.9 GJ | Energy content of 1 metric tonne (1,000 kg, roughly 1 English ton) of oil. (1 GJ = $10^9$ J) |
| barrel of oil equivalent (boe) | 6.12 GJ | Energy content of one 42-gallon barrel of oil. |

| Power units | Watt equivalent | Description |
|---|---|---|
| watt (W) | 1 W | Equivalent to 1 J/s. |
| horsepower (hp) | 746 W | Unit derived originally from power supplied by horses; now used primarily to describe engines and motors. |
| Btu per hour (Btu/h, or Btuh) | 0.293 W | Used primarily in the United States, usually to describe heating and cooling systems. |

*See Table 3.2 for SI prefixes.

## BOX 3.1 | Converting Units

With many different energy units, it's important to know how to convert from one unit to another. The trick is to multiply by a ratio—which you can find or work out from Table 3.1—that gives the final unit you want. For example, to convert the U.S. annual energy consumption of about 100 Q to exajoules (EJ), note Table 3.1's conversion factor for the quad, which can be written as a ratio: 1.054 EJ/Q. Then our conversion for 100 Q becomes

$$(100\ \mathrm{Q})(1.054\ \mathrm{EJ/Q}) = 105\ \mathrm{EJ}$$

Note how the Q "upstairs"—in the numerator of the term 100 Q—cancels with the Q "downstairs" in the term 1.054 EJ/Q. That leaves the final unit as EJ, which is what we want. Since that 100 Q was a yearly energy consumption, we can write the U.S. energy consumption rate as 105 exajoules per year (EJ/y).

That 105 EJ/y describes energy per time, so it's a measure of *power*. Suppose I want to convert it to horsepower: Table 3.1 lists 1 horsepower (hp) as 746 watts (W). A watt is a joule per second, so we'll first convert 105 EJ/y to joules per second (J/s). A year is about $3.15 \times 10^7$ seconds (you can get this by multiplying 365 days/year by 24 hours/day by 3,600 seconds/hour), and an exajoule, as Table 3.1 implies, is $10^{18}$ joules. So our 105 EJ/y becomes

$$\frac{(105\ \mathrm{EJ/y})(10^{18}\ \mathrm{J/EJ})}{3.15\times10^{7}\ \mathrm{s/y}} = 3.33\times10^{12}\ \mathrm{J/s}$$
$$= 3.33\times10^{12}\ \mathrm{W}$$

Now we convert that to horsepower (hp), using 746 W/hp from Table 3.1. Since we want horsepower "upstairs" in our final answer, we need to *divide* by this conversion factor, in which horsepower appears "downstairs." So we have

$$\frac{3.33\times10^{12}\ \mathrm{W}}{746\ \mathrm{W/hp}} = 4.46\times10^{9}\ \mathrm{hp}$$

That makes the United States a nearly 5-billion horsepower country!

## EXAMPLE 3.1 | Home Heating

Assuming home heating oil contains about 40 kWh of energy per gallon, determine the approximate rate of oil consumption in my home furnace when it's producing heat at the rate of 112,000 Btu/h.

### SOLUTION

We have the oil's energy content in kilowatt-hours, so we need to convert that 112,000 Btu/h into compatible units, in this case kilowatts. Table 3.1 shows that 1 Btu is 1,054 J, or 1.054 kJ, and one hour is 3,600 seconds, so the heat output of the furnace becomes

$$(112{,}000\ \mathrm{Btu/h})(1.054\ \mathrm{kJ/Btu})(1\mathrm{h}/3{,}600\ \mathrm{s}) = 33\ \mathrm{kJ/s} = 33\ \mathrm{kW}$$

Notice how I was careful to write out all the units and to check that they multiplied together to give the correct final unit:

$$(\mathrm{Btu/h})(\mathrm{kJ/Btu})(\mathrm{h/s}) \rightarrow \mathrm{kJ/s} = \mathrm{kW}$$

In any numerical problem like this one, it's essential that the units work out correctly. If they don't, the answer is wrong, even if you did the arithmetic correctly. Note in this case that the unit for hour (h) is in the denominator, so I had to multiply by hours per second (h/s) to convert the time unit to seconds.

So my furnace produces heat at the rate of 33 kW, or 33 kWh/h. Since there are 40 kWh of energy in a gallon of oil, the furnace would need to burn a little over three-quarters of a gallon per hour (33/40) if it were perfectly efficient. But it isn't, so that 112,000 Btu/h heat output requires close to 1 gallon of oil per hour.

Table 3.1 lists several other energy units that we'll have little use for in this book, but that often appear in the scientific literature. The erg is the official unit of the centimeter-gram-second system of units (as opposed to the SI

## BOX 3.2 | SI Prefixes

Units for energy and other quantities are often modified with prefixes that indicate multiplication by powers of 10; every three powers gets a new name. You've already met kilo (k, meaning 1,000 or $10^3$) and mega (M, 1 million or $10^6$). Others you've probably heard are giga (G, 1 billion or $10^9$), milli (m, 1/1,000 or $10^{-3}$), micro ($\mu$, the Greek "mu," one-millionth or $10^{-6}$), and nano (n, one-billionth or $10^{-9}$). Table 3.2 lists others, all part of the SI unit system. The large multipliers are useful in quantifying the huge rates of energy consumption in the industrialized world. The world total of 470 Q per year, for example, can be expressed in SI as about 500 exajoules (EJ) per year; converting to watts (Exercise 3) gives a world energy-consumption rate of about 16 terawatts (16 TW, or $16 \times 10^{12}$ W). I'll use SI prefixes routinely throughout this book, and you can find them here in Table 3.2 and also inside the back cover. Note that the symbols for SI prefixes that multiply by less than 1 are in lowercase, while those that multiply by more than 1 (except for kilo) are capitalized.

### TABLE 3.2 | SI PREFIXES

| Multiplier | Prefix | Symbol |
|---|---|---|
| $10^{-24}$ | yocto | y |
| $10^{-21}$ | zepto | z |
| $10^{-18}$ | atto | a |
| $10^{-15}$ | femto | f |
| $10^{-12}$ | pico | p |
| $10^{-9}$ | nano | n |
| $10^{-6}$ | micro | $\mu$ |
| $10^{-3}$ | milli | m |
| $10^{0}$ (= 1) | — | — |
| $10^{3}$ | kilo | k |
| $10^{6}$ | mega | M |
| $10^{9}$ | giga | G |
| $10^{12}$ | tera | T |
| $10^{15}$ | peta | P |
| $10^{18}$ | exa | E |
| $10^{21}$ | zeta | Z |
| $10^{24}$ | yotta | Y |

meter-kilogram-second units). The electron volt is a tiny unit ($1.6 \times 10^{-19}$ J) used widely in nuclear, atomic, and molecular physics. Finally, the foot-pound is an English unit, being the energy expended when you push on an object with a force of 1 pound as the object moves 1 foot.

The last two energy units in Table 3.1 deserve special mention because they're based not directly on energy but on oil. The **tonne oil equivalent** is the energy content of a metric ton of typical oil, while the **barrel of oil equivalent** is the energy content of a standard 42-gallon barrel. (A **metric ton**, also called a **tonne**, is equal to 1,000 kg or a little more than a 2,000-lb U.S. **ton**.) The values given for the tonne oil equivalent and barrel of oil equivalent in Table 3.1 are formal definitions; the actual energy content of oil varies somewhat, depending on its source and composition.

Table 3.1 also lists several units for power. Among those in common use is **horsepower** (hp), a holdover from the day when horses supplied much of the energy coming from beyond our own bodies. One horsepower is 746 W, or about three-quarters of a kilowatt. So a 400-hp car engine can, in principle, supply energy at the rate of about 300 kW (most of the time the actual rate may be much less, and very little of that energy ends up propelling the car; more on this in Chapter 5).

Fuels—those substances that store potential energy in the configurations of molecules or atomic nuclei—are characterized by their energy content, expressed as energy contained in a given mass or volume. Table 3.3 lists the energy contents of some common fuels. Some of these quantities find their way into alternative units for energy and for energy-consumption rate, as in the tonne oil equivalent and barrel of oil equivalent listed in Table 3.1. Related power units of millions of barrels of oil equivalent per day often describe the production of fossil fuels, and national energy-consumption rates are sometimes given in millions of barrels of oil equivalent per year. At a smaller scale, it's convenient to approximate the energy content of a gallon of petroleum product—oil, kerosene, gasoline—as being about 40 kWh (the exact amount varies with the fuel, and the amount of useful energy obtained depends on the efficiency of the energy-conversion process). Finally, Table 3.3 hints at the huge quantitative difference between chemical and nuclear fuels; just compare the energy per kilogram of petroleum with that of uranium!

You'll find Tables 3.1 through 3.3 sufficiently useful that they're printed inside the front and back covers for easy reference, along with other useful energy-related information.

## 3.4 Energy and Work

Push a stuck car out of the mud, a lawnmower through tall grass, or a heavy trunk across the floor, and in all cases you're doing a lot of work. **Work** has a precise scientific meaning: It's a quantity equal to the force you apply to an object multiplied by the distance over which you move that object. Work is essentially a measure of the energy you expend as you apply a force to an object. This energy may end up as increased kinetic energy of the object, as when you kick a soccer

TABLE 3.3 | **ENERGY CONTENT OF FUELS**

| Fuel | Typical energy content (varies with fuel source): SI units | Other units |
|---|---|---|
| Coal | 29 MJ/kg | 7,300 kWh/ton<br>25 MBtu/ton |
| Oil | 43 MJ/kg | ~40 kWh/gallon<br>138 kBtu/gallon |
| Gasoline | 44 MJ/kg | 36 kWh/gallon |
| Natural gas | 55 MJ/kg | 30 kWh/100 cubic feet<br>1,000 Btu/cubic foot |
| Biomass, dry | 15–20 MJ/kg | 13–17 MBtu/ton |
| Hydrogen gas ($H_2$) burned to produce $H_2O$ | 142 MJ/kg | 320 Btu/cubic foot |
| Uranium, nuclear fission: | | |
| Natural uranium | 580 GJ/kg | 161 GWh/tonne |
| Pure U-235 | 82 TJ/kg | 22.8 TWh/tonne |
| Hydrogen, deuterium-deuterium nuclear fusion: | | |
| Pure deuterium | 330 TJ/kg | |
| Normal water | 12 GJ/kg | 13 MWh/gallon,<br>350 gallons gasoline equivalent per gallon water |

ball and set it in motion, or it may end up as potential energy, as when I lifted that bowling ball over your head. One caveat: You do work only when the force you apply to an object is in the direction of the object's motion. If the force is at right angles to the motion, no work is done, and there's no change in the object's energy. If the force is opposite the motion, then the work is negative and you take energy away from the object. Figure 3.9 illustrates these possibilities.

So work is a measure of energy supplied to an object by mechanical means—that is, by applying a force, such as pushing or pulling. Again, it's the product of force times the distance the object moves:

$$W = Fd \tag{3.2}$$

Here $W$ is the work, $F$ the force, and $d$ the distance. Equation 3.2 applies in the case where the force and the object's motion are in the same direction. In the

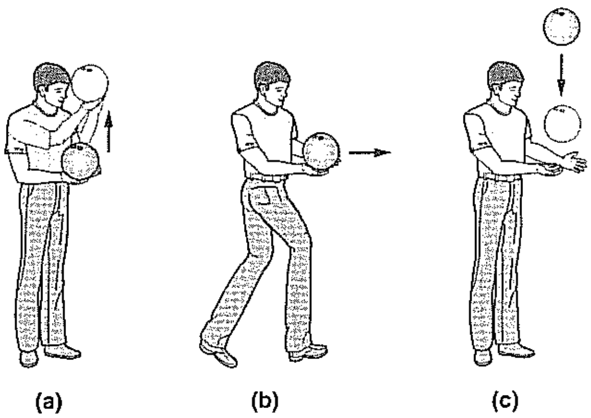


FIGURE 3.9

Force and work. (a) When you lift a bowling ball, you apply a force in the direction of its motion. You do work on the ball, in this case increasing its gravitational potential energy. (b) When you carry the ball horizontally, you apply a force to counter its weight, but you don't do work on the ball because the force is at right angles to its motion. (c) When you apply an upward force to stop a falling ball, the force is opposite the ball's motion, so here you do negative work that reduces the ball's kinetic energy.

English system commonly used in the United States, force is measured in pounds and distance in feet; hence the English unit of work is the foot-pound (see Table 3.1). In the SI system, the unit of force is the **newton** (N), named in honor of the great physicist Isaac Newton, who formulated the laws governing motion. One newton is roughly one-fifth of a pound (1 pound = 4.48 N). The SI unit of distance is the meter, so work is measured in newton-meters (N·m). And what's a newton-meter? Since work is a measure of energy transferred to an object, 1 N·m is the SI unit of energy, namely the joule. So another way of understanding the joule is to consider it the energy supplied by exerting a force of 1 N on an object as the object moves a distance of 1 m.

An object's **weight** is the force that gravity exerts on it. Near Earth's surface, the strength of gravity is such that an object experiences a force of 9.8 N for every kilogram of mass it possesses. We designate this quantity $g$, the strength of gravity near Earth's surface. The value of $g$ is then 9.8 newtons per kilogram (N/kg), which is close enough to 10 N/kg that I'll frequently round it up. (If you've had a physics course, you probably know $g$ as the acceleration of gravity—the rate at which an object falling near Earth's surface gains speed. My definition here is equivalent, but more useful for thinking about energy.) We can sum all this up mathematically: If an object has mass $m$, then its weight is given by

$$F_g = mg \tag{3.3}$$

Here I've designated weight as $F_g$, for "force of gravity," because I've already used the symbol $W$ for work. If $m$ is in kilograms and $g$ in newtons per kilogram, then the weight is in newtons.

To lift an object at a steady rate, you have to apply a force that counters the force of gravity. That is, the force you apply is equal to the object's weight, which Equation 3.3 shows is simply the product $mg$. Suppose you lift the object a height $h$. Using $h$ for the distance in Equation 3.2, we can then combine Equations 3.2 and 3.3 to get an expression for the work you do in lifting the object:

$$W = mgh \tag{3.4}$$

This work ends up being stored as gravitational potential energy. Since the gravitational force "gives back" stored potential energy, Equation 3.4 also describes the kinetic energy gained when an object with mass $m$ falls a distance $h$.

Earlier I suggested that you could get a feel for the size of a joule by lifting your 2-pound book about 4 inches. Two pounds is about 1 kg, so your book's weight is about 10 N (here I multiplied 1 kg by the approximate value for $g$, namely 10 N/kg). Four inches is about 10 centimeters (cm), or one-tenth of a meter, so Equation 3.2 gives $W = (10\text{ N}) \times (0.10\text{ m}) = 1.0\text{ J}$. Or just derive it from Equation 3.4:

$$W = mgh = (1\text{ kg})(10\text{ N/kg})(0.10\text{ m}) = 1\text{ J}$$

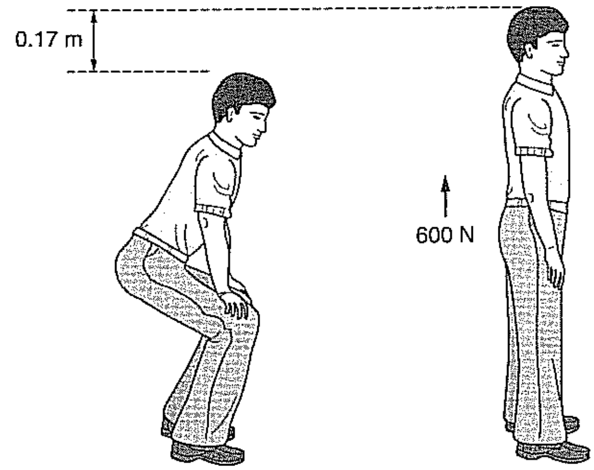


**FIGURE 3.10**
Rising out of a knee bend requires that I apply a 600-N force over a distance of 0.17 m, resulting in 100 J of work done. Repeating once per second gives a power output of 100 W.

So there it is: Lift your 2-pound book 4 inches and you've done one 1 J of work, giving the book 1 J of gravitational potential energy.

What's your weight? My mass is about 70 kg, so according to Equation 3.3 my weight is (70 kg) × (10 N/kg) = 700 N. With 4.48 N per pound, this is equivalent to (700 N)/(4.48 N/lb) = 156 lb. That's just what my U.S. scale reads. Suppose I start doing those knee bends from Chapter 2. I've marked the position of the top of my head on a chalkboard when standing and again when at the lowest point of my knee bend, and the marks are 17 cm apart (0.17 m) (Fig. 3.10). So as I come up out of each knee bend, I raise most of my weight by 17 cm. Most? Yes: My feet stay on the ground and my legs participate in only some of the motion. So the weight that's actually raised is somewhat less than my actual weight; suppose it's about 600 N. Then each time I rise to my full height, the work I do is $W$ = (600 N) × (0.17 m) ≈ 100 N·m ≈ 100 J. If I do those knee bends once every second, that's 100 J/s, or 100 W. Again, this is a rough figure; you could quibble with my choice for just what fraction of my weight I actually raise, and surely the once-per-second is only approximate. But there it is: While doing those knee bends, my body expends energy at the rate of roughly 100 W.

You might wonder what happens as I lower my body when bending my knees. In that downward motion I do negative work, or the force of gravity does work on me. If my muscles were like springs, this energy would be stored as elastic potential energy and be available for the next upward motion, with the result that my overall energy output would be considerably less. But my muscles aren't springs, and most of that energy is lost in heating the muscles and other body tissues. There's a little bit of springlike energy storage in muscles, but it isn't very significant with the relatively slow muscle contractions and extensions of this knee-bend exercise.

## EXAMPLE 3.2 | Mountain Run!

(a) How much work do I do in running up a mountain with a vertical climb of 2,500 feet (760 m)? Express the answer in both joules and calories. (b) If the run takes 50 minutes, what's the average power involved?

### SOLUTION

My mass is 70 kg, $g$ is 9.8 N/kg, and I'm climbing 760 m; Equation 3.4 then gives

$$W = mgh = (70\ \text{kg})(9.8\ \text{N/kg})(760\ \text{m}) = 521\ \text{kJ}$$

With 1 kcal = 4.184 kJ, this amounts to (521 kJ)/(4.184 kJ/kcal) = 125 kcal. This is the bare minimum amount of work it would take to scale the mountain because my body is far from 100% efficient, and I do work against frictional forces in my own muscles even when walking horizontally. So I probably burn up a lot more than the 125 "calories"—actually kilocalories—implied by this answer.

Expending those 521 kJ over 50 minutes gives an average power of

$$p = \frac{521 \text{ kJ}}{(50 \text{ min})(60 \text{ s/min})} = 0.174 \text{ kJ/s} = 174 \text{ W}$$

Again, the actual rate of energy expenditure would be a lot higher, although it might take rather more than 50 minutes to make a 2,500-foot climb.

## 3.5 Work and Kinetic Energy

The examples of the preceding section involved our doing work against the gravitational force, resulting in stored gravitational energy. But what if there is no opposing force? Then the work we do on an object goes into kinetic energy. Examples include pushing a fellow skater or hockey puck on ice, kicking a ball on a smooth horizontal surface, or accelerating a car from a stoplight.

An important result, which follows from Newton's laws of motion, is the **work–energy theorem**. It states that the *net work* done on an object—that is, the total work done by all the forces acting—is equal to the change in the object's kinetic energy. The theorem specifically identifies the kinetic energy $K$ with the quantity $\frac{1}{2}mv^2$, where $m$ is the mass and $v$ (for velocity) is its speed:

$$K = \tfrac{1}{2}mv^2 \qquad \text{(kinetic energy)} \qquad (3.5)$$

It's important to recognize that the work–energy theorem applies not to individual forces, but only to the sum of all forces acting on an object. For example, you do work lifting an object at constant speed against gravity, but the downward-acting gravitational force does negative work, and the *net work* is zero. Thus the object's kinetic energy doesn't change—although the work you've done has increased its potential energy. But if you kick a ball horizontally with a force that exceeds the frictional force, then the positive work you do exceeds the negative work done by friction; thus the net work is positive and the ball's kinetic energy $\frac{1}{2}mv^2$ increases—and so, therefore, does its speed $v$.

Note that the kinetic energy depends on an object's speed *squared*, which means kinetic energy increases rapidly with speed. For example, doubling the speed (a factor of 2) results in quadrupling the energy (a factor of $2^2$, or 4). That's one reason why driving at high speeds is particularly dangerous, more so than if energy increased in direct proportion to speed (Fig. 3.11). And it's also why accelerating rapidly to high speeds is a rather inefficient use of fuel.

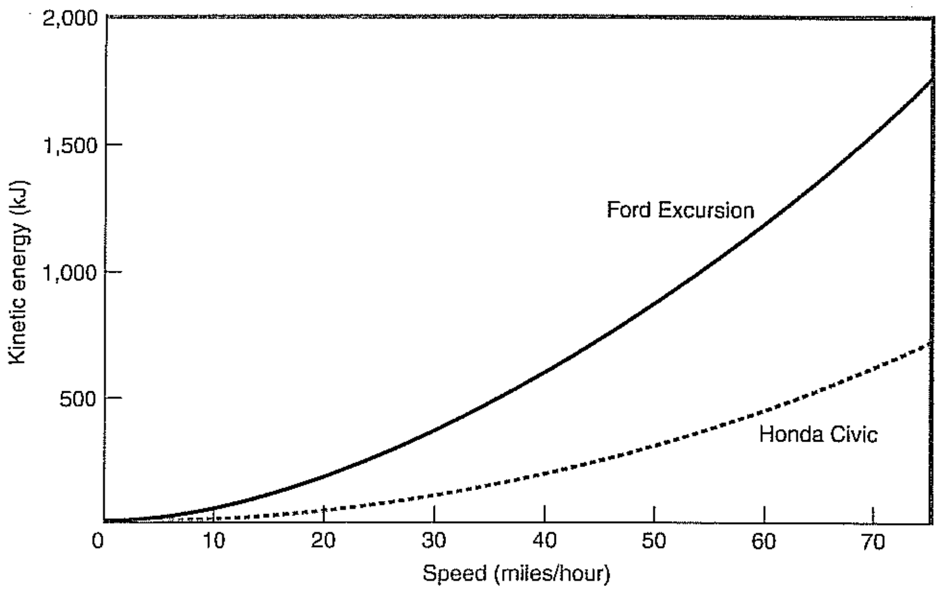


**FIGURE 3.11**
Kinetic energy increases with the square of the speed. Shown here is kinetic energy versus speed for a Honda Civic compact car (empty weight 1,268 kg) and a Ford Excursion SUV (empty weight 3,129 kg), each with a 68-kg driver. The weight difference accounts for much of the difference in fuel efficiency between these vehicles.

## EXAMPLE 3.3 | Takeoff Power!

A fully loaded Boeing 767-300 jetliner has a mass of 180,000 kg. Starting from rest, it accelerates down the runway and reaches a takeoff speed of 270 kilometers per hour (km/h) in 35 seconds. What engine power is required for this takeoff roll?

### SOLUTION

The plane gains kinetic energy during the takeoff roll, and we know how long the roll takes, so we can calculate the energy per time, or power. Equation 3.5 gives energy in joules if the mass is in kilograms and speed is in meters per second. So first we convert that 270 km/h into meters per second:

$$(270\ \text{km/h})(1{,}000\ \text{m/km})(1\ \text{h}/3{,}600\ \text{s}) = 75\ \text{m/s}$$

Then the plane's kinetic energy at takeoff is

$$K = \tfrac{1}{2}mv^2 = \left(\tfrac{1}{2}\right)(180{,}000\ \text{kg})(75\ \text{m/s})^2 = 5.1 \times 10^8\ \text{J} = 510\ \text{MJ}$$

The plane is on the runway for 35 seconds, so the engines must be supplying power at the rate of 510 MJ/35 s = 14.6 MJ/s or 14.6 MW. With 1 hp being 746 W, that's about 20,000 hp.

## 3.6 The Role of Friction

We've now seen that doing work on an object generally results in either stored potential energy or increased kinetic energy (or both if, for example, you simultaneously lift and accelerate an object). But there's one case where doing work increases neither potential nor kinetic energy. That's when you do work solely to overcome friction. When I lifted that bowling ball over your head, you were worried because you knew that the gravitational force would "give back" the stored potential energy if I let go of the ball. But if you push a heavy trunk across a level floor, you don't have to worry about the trunk sliding back and doing damage once you let go. Why not? Because the energy you expended pushing the trunk didn't end up as stored potential energy. But energy is conserved, so where did it go? Most of it went into the form of energy we call, loosely, "heat." Unlike the case of lifting an object or compressing a spring, that energy became unavailable for conversion back to kinetic energy. To convince yourself that friction turns mechanical energy into heat, just try rubbing your hands rapidly together!

The **frictional force** is fundamentally different from forces like gravity or the force in a spring, in that work done against friction doesn't end up as stored potential energy. Rather, it ends up in a form—"heat"—that isn't particularly useful. This inability to recover the energy "lost" to friction is an important limitation on our efforts to use energy wisely and efficiently. For example, despite our best engineering efforts, much of the mechanical energy extracted from gasoline in a typical automobile is lost to friction in the engine, transmission, and tires.

## 3.7 The Art of Estimation

In this chapter I've thrown around a lot of numbers and a few equations, because it's important to be able to calculate, and calculate accurately, when dealing quantitatively with energy. But it's equally important to be able to make a quick, rough, "back of the envelope" estimate. This kind of estimate won't be exactly right, but it should be close enough to be useful. Many times that's all you need to appreciate an important energy concept or quantity. Below are a couple of examples of estimation. Note how readily I've approximated quantities to nice, round numbers or guessed quantities I wasn't sure of.

### EXAMPLE 3.4 | Lots of Gasoline

What's the United States' annual gasoline consumption?

SOLUTION

How many cars are there in the United States? I don't know, but I do know that there are around 300 million people. Americans love cars, so I'm guessing there are around 200 million cars, vans, SUVs, and pickup trucks. How far does a typical car go in one year? More than a few thousand miles, but (for most of us), not 50,000 or 100,000 miles. So suppose it's about 10,000 miles.

And what's the average fuel efficiency in the United States? After falling from the 1980s through 2004, it's risen slightly and now averages about 25 miles per gallon for cars, vans, SUVs, and pickups. Using that figure, the U.S. gasoline consumption rate is

$$(200 \times 10^6 \text{ cars})(10^4 \text{ miles/car/year})\left(\frac{1}{25 \text{ miles/gallon}}\right) = 8 \times 10^{10} \text{ gallons/year}$$

Note my use of scientific notation to make dealing with big numbers easier. I rounded the final result to just one digit because this is an estimate; I could have rounded further to $10^{11}$ gallons per year because the numbers going into my estimate were so imprecise. How did I know to put the 25 miles per gallon in the denominator? Two ways: First, it makes the units come out right, as they must. I was asking for gallons per year, so I'd better do a calculation that gives gallons per year. Second, and a bit more physically meaningful, I know that higher fuel efficiency should result in lower fuel consumption, so the fuel efficiency had better be in the denominator. More cars and more miles driven increase consumption, so they go in the numerator.

How good is this estimate? According to the U.S. Energy Information Administration (EIA), U.S. gasoline consumption in 2010 was about 380 million gallons per day. Multiplying by 365 days per year gives $1.4 \times 10^{11}$ gallons. My estimate, just under $10^{11}$ gallons per year, is a bit low but certainly in the ballpark. And the EIA figure includes gasoline-powered commercial trucks as well as private vehicles. By the way, the number of cars, SUVs, and light trucks registered in the United States in 2010 was about 250 million—above my estimate of 200 million and close to one vehicle for every adult and child!

## EXAMPLE 3.5 | A Solar-Powered Country?

The average rate at which Earth's surface absorbs solar energy is about 240 W/m$^2$—that is, 240 watts on each square meter of surface area (this figure accounts for night and day, reflection off clouds, and other factors). If we had devices capable of capturing this energy with 100% efficiency, how much area would be needed to supply the total U.S. energy demand?

### SOLUTION

At what rate does the United States use energy? The U.S. population is about 300 million, and, as we saw in the preceding chapter, U.S. residents consume energy at the rate of about 10 kW per capita. So the area needed would be:

$$(300 \times 10^6 \text{ people})(10^4 \text{ W/person})\left(\frac{1}{240 \text{ W/m}^2}\right) = 10^{10} \text{ m}^2$$

where I rounded 300/240 to 1, and put the watts per square meter in the denominator for the same reason I did the miles per gallon in the previous example. There are 1,000 meters or $10^3$ m in 1 km, so there are $10^6$ $m^2$ in 1 $km^2$ (picture a square 1,000 m on a side; it contains a million little squares each 1 m × 1 m). So that $10^{10}$ $m^2$ is $10^4$ $km^2$. For comparison, that's roughly one-sixth the area of California's Mojave Desert. Of course we don't have solar energy conversion devices that are 100% efficient, so considerably more area would actually be needed—perhaps 10 times as much with efficiency and infrastructure taken into account. Still, the required land area is remarkably small. See Research Problem 4 for more on this point.

## 3.8 Wrapping Up

This chapter examines basic energy concepts at the most fundamental level; in that sense it's both essential for and yet most removed from the main themes of this book, namely human energy use and its environmental impacts. You now understand that energy manifests itself either as the kinetic energy associated with motion, or as potential energy associated with forces such as gravity, electromagnetic forces, and nuclear forces. You understand conceptually how energy is stored as gravitational potential energy or as chemical or nuclear energy in fuels. And you know how to talk fluently about energy and power in a variety of unit systems. Finally, you can calculate potential and kinetic energies in simple systems, determine power consumption, and make quick estimates of energy-related quantities.

Still, something may seem missing. Have we really covered all forms of energy? In one sense, yes. But in another, no: We haven't said much about that form of energy called, loosely, "heat." That's a topic with big implications for our human energy consumption, and it's the subject of the next chapter.

# CHAPTER REVIEW

### BIG IDEAS

**3.1** Many forms of energy are instances of **kinetic energy** or **potential energy**. Kinetic energy is the energy of moving objects, while potential energy is stored energy.

**3.2** Electricity and magnetism play a crucial role in energy storage and energy technologies. The energy of chemical fuels is ultimately stored in the electric fields associated with molecular configurations. The electric power we use is produced through the process of **electromagnetic induction**. Electromagnetic energy is also carried by **electromagnetic radiation**, of which light is an important example.

**3.3** The watt (W) is the standard unit of power, and the **joule** (J) is the corresponding energy unit. One watt is 1 joule per second (J/s). Other common energy units include the kilowatt-hour (kWh), **calorie** (cal), and **British thermal unit** (Btu). Multiples of units are expressed with standard prefixes, and conversion factors relate energy measurements in different units.

**3.4** You do **work** when you apply a force to an object as it moves, provided the force acts in the direction of the object's motion. Work is the product of the force and the distance the object moves. Doing work on an object increases its energy. For example, applying a force to lift an object results in an increase in its gravitational potential energy.

**3.5** An object of mass $m$ moving with speed $v$ has kinetic energy $K = \frac{1}{2}mv^2$. The **work–energy theorem** states that kinetic energy changes only when nonzero *net work* is done on the object. The net work includes work done by *all* forces acting on the object; if the net work is positive, then kinetic energy increases.

**3.6** Friction is a force that dissipates energy, turning the energy of motion into less useful forms. Friction can limit our ability to use energy efficiently.

**3.7** Energy is a quantitative subject. However, you can learn a lot about energy with quick, simple estimates of numerical quantities.

## TERMS TO KNOW

barrel of oil equivalent (p. 50)
battery (p. 39)
British thermal unit (p. 46)
calorie (p. 46)
chemical energy (p. 42)
elastic potential energy (p. 36)
electric charge (p. 39)
electric current (p. 39)
electric field (p. 39)
electromagnetic force (p. 37)
electromagnetic induction (p. 40)
electromagnetic radiation (p. 43)
electromagnetic wave (p. 43)
force (p. 37)
frictional force (p. 56)
fuel cell (p. 40)
gravitational force (p. 37)
gravitational potential energy (p. 36)
horsepower (p. 50)
joule (p. 45)
kinetic energy (p. 36)
magnetic field (p. 39)
newton (p. 52)
nuclear force (p. 37)
photon (p. 44)
photovoltaic cell (p. 42)
Planck's constant (p. 44)
potential energy (p. 36)
quad (p. 46)
rechargeable battery (p. 40)
ton, tonne, metric ton (p. 50)
tonne oil equivalent (p. 50)
weight (p. 52)
work (p. 50)
work–energy theorem (p. 54)

## GETTING QUANTITATIVE

Energy of a photon: $E = hf = \frac{hc}{\lambda}$ (Equation 3.1; p. 44)

Planck's constant: $h = 6.63 \times 10^{-34}$ J·s

Speed of light: $c = 3.00 \times 10^8$ m/s

Energy and power units: see Table 3.1

Energy content of fuels: see Table 3.3

Work: $W = Fd$ (Equation 3.2; p. 51)

Force of gravity: $F_g = mg$ (Equation 3.3; p. 52)

Work done lifting object of mass $m$ a distance $h$: $W = mgh$ (Equation 3.4; p. 52)

Kinetic energy: $K = \frac{1}{2}mv^2$ (Equation 3.5; p. 54)

## QUESTIONS

1 Why is it harder to walk up a hill than on level ground?

2 Describe qualitatively the relationship between force and potential energy.

3 Table 3.3 shows that hydrogen has a higher energy content per kilogram than natural gas, but a lower energy content per cubic foot. How can this be consistent?

4 You jog up a mountain and I walk. Assuming we weigh the same, compare (a) our gravitational potential energies when we're at the summit, and (b) the average power each of us expends in climbing the mountain.

5 How many (a) megajoules are in 1 exajoule; (b) petagrams in 1 gigatonne (1 tonne = 1,000 kg); (c) kilowatt-hours in 1 gigawatt-hour?

6 How is the frictional force fundamentally different from the gravitational force?

## EXERCISES

1 The average daily human diet has an energy content of about 2,000 kcal. Convert this 2,000 kcal per day into watts.

2 Using appropriate conversions between pounds and grams, and degrees Celsius and Fahrenheit, show that 1 Btu is equivalent to 1,054 J.

3 Express in watts the world energy-consumption rate of approximately 470 Q per year.

4 There are two ways to calculate the power output of a car when you know that (1) the car has a 250-horsepower engine and (2) the car gets 20 miles per gallon when traveling at 60 miles per hour: (a) Convert the horsepower rating into watts. (b) Calculate the gasoline consumption rate and, using Table 3.3's energy equivalent for gasoline, convert the result to a power in watts. Comparison of your results shows that a car doesn't always achieve its engine's rated horsepower.

5 An oil furnace consumes 0.80 gallons of oil per hour while it's operating. (a) Using the approximate value of 40 kWh per gallon of petroleum product, find the equivalent power consumption in watts. (b) If the furnace runs only 15% of the time on a cool autumn day, what is the furnace's average power consumption?

6 The United States imports about 12 million barrels of oil per day. (a) Consult the tables in this chapter to convert this quantity to an equivalent power, measured in watts. (b) Suppose we wanted to replace all that imported oil with energy produced by fission from domestic uranium. How many 1,000-MW nuclear power plants would we have to build?

7 Assuming that 1 gallon of crude oil yields roughly 1 gallon of gasoline, estimate the decrease in daily oil imports (see preceding question) that we could achieve if the average fuel efficiency of U.S. cars and light trucks, now around 23 miles per gallon, were raised to the 50 miles per gallon typical of a hybrid car. Assume the average vehicle is driven about 10,000 miles per year and that there are about 250 million cars and light trucks operating in the United States.

8 In the text I cited an environmentalist's claim that buying an SUV instead of a regular car wastes as much energy as leaving your refrigerator door open for 7 years. Let's see if that's right. A typical refrigerator consumes energy at the rate of about 400 W when it's running, but it usually runs only about a quarter of the time. If you leave the door open, however, the refrigerator will run all the time. Assume that an average SUV's fuel efficiency is 20 miles per gallon, an average car gets 30 miles per gallon, gasoline contains 40 kWh of energy per gallon, and you drive the vehicle 15,000 miles per year. Calculate how long you would have to leave your refrigerator door open to use as much extra energy as the difference between the car and SUV in the first year you own the vehicle.

9 I want to expend 100 "calories" (that is, 100 kcal) of energy working out on an exercise machine. The readout on the machine says I'm expending energy at the rate of 270 W. How long do I need to exercise to expend those 100 kcal?

10 You buy a portable electric heater that claims to put out 10,000 Btuh (meaning 10,000 Btu/h). If it's 100% efficient at converting electrical energy to heat, what is its electrical energy-consumption rate in watts?

11 A car with a mass of 1,700 kg can go from rest to 100 km/h in 8.0 seconds. If its energy increases at a constant rate, how much power must be applied to achieve this magnitude of acceleration? Give your answer in both kilowatts and horsepower.

12 You're cycling on a level road at a steady 12 miles/hour (5.4 m/s), and your body's mechanical power output is 150W. Because your speed is constant, you're applying a force that's just enough to overcome the forces of friction and air resistance. What is the value of your applied force?

13 You're cycling up a hill, rising 5 feet for every 100 feet you move along the road. You're going at a steady 4.3 m/s, and you need to overcome frictional forces totalling 30 N. If you and your bicycle together have a mass of 82 kg, what's the minimum power you need to supply to overcome both friction and gravity?

14 An energy-efficient refrigerator consumes energy at the rate of 280 W when it's actually running, but it's so well insulated that it runs only about one-sixth of the time. You pay for that efficiency up front: It costs $950 to buy the refrigerator. You can buy a conventional refrigerator for $700. However, it consumes 400 W when running, and it runs one-fourth of the time. Calculate the total energy used by each refrigerator over a 10-year lifetime and then compare the total costs—purchase price plus energy cost—assuming electricity costs 10¢ per kilowatt-hour.

15 In 2010 the *Deepwater Horizon* oil well in the Gulf of Mexico blew out, spilling some 5 million barrels of oil into the Gulf over 3 months. (a) Find the energy equivalent of the spilled oil, in joules or suitable multiples, and (b) estimate how long this oil could have supplied the entire U.S. energy demand.

## RESEARCH PROBLEMS

1 Find a value for the current population of the United States, and use your result along with the approximate U.S. annual energy-consumption rate of 100 Q per year to get an approximate value for the per capita U.S. energy-consumption rate in watts.

2 Choose a developing country and find the values for its current population and its total annual energy consumption in quads. Using these numbers, calculate the per capita energy-consumption rate in watts.

3 Find the official EPA (Environmental Protection Agency) fuel efficiency for the car you or your family drive. Estimate your yearly mileage, and determine the amount of fuel you would save each year if you switched to a 50-mile-per-gallon hybrid.

4 Make the assumption that the solar-collector area calculated in Example 3.5 should be increased by a factor of 10 to account for the inefficiency of the solar cells and to allow room for infrastructure. What fraction of the total area of (a) the state of New Mexico and (b) the continental United States would then be needed? (c) Compare your answer to part (b) with the fraction of land that's now under pavement.

## ARGUE YOUR CASE

1 A friend claims that a metric tonne is more than twice the mass of an English ton, since a kilogram is more than twice the mass of a pound. Make a quantitative argument in support of or against your friend's claim.

2 Upgraded fuel economy standards released in 2010 call for a 34.1 mile-per-gallon average for new cars and light trucks in 2016. A politician opposing this increase claims it will save "only a drop in the bucket" compared with the 2010 fleet average of about 23 MPG. Formulate a counterargument showing that the increase—once the entire fleet reaches 34.1 MPG—could significantly reduce the United States' gasoline consumption rate from its 2010 value of about 380 million gallons per day. State any additional assumptions you make.