Chapter 1

What is Energy?

We hear about energy everywhere.

The newspaper tells us that California has an energy crisis, and that the President of the United States has an energy plan. The Vice President, meanwhile, says that conserving energy is a personal virtue. We pay bills for energy every month, but an inventor in Mississippi claims to have a device that provides "free" energy. Athletes eat high-energy foods, and put as much energy as they can into the swing or the kick or the sprint. A magazine carries an advertisement for a "certified energy healing practitioner," whose private, hands-on practice specializes in the "study and exploration of the human energy field."

Like most words, "energy" has multiple meanings. This course is about the *scientific* concept of energy, which is fairly consistent with most, but not all, of the meanings of the word in the preceding paragraph.

What *is* energy, in the scientific sense? I'm afraid I don't really know. I sometimes visualize it as a substance, perhaps a fluid, that permeates all objects, endowing baseballs with their speed, corn flakes with their calories, and nuclear bombs with their megatons. But you can't actually *see* the energy itself, or smell it or sense it in any direct way—all you can perceive are its *effects*. So perhaps energy is a fiction, a concept that we invent, because it turns out to be so useful.

Energy can take on many different forms. A pitched baseball has **kinetic energy**, or energy of motion. When the ball is high above the ground, we say it has **gravitational energy**. Stretching a rubber band stores **elastic energy** in it. Corn flakes and gasoline store **chemical energy**, while uranium and plutonium store **nuclear energy**. A hot potato contains more **thermal energy** than it did when it was cold. **Electrical energy** is transmitted along wires from power plants to appliances, and **radiant energy** is given off by lightbulbs, lasers, stovetops, and stars. Figure 1.1 lists the most important types of energy and their physical manifestations.

These multiple forms of energy can be *converted* into each other. As the baseball flies upward, its kinetic energy is converted into gravitational energy; as it falls, the gravitational energy is converted back into kinetic energy. Before the energy entered the ball, it was stored as chemical energy in the batter's breakfast. When the ball hits the ground and rolls to a stop, its kinetic energy is converted into thermal energy, warming the ball and the ground very slightly. A slingshot converts elastic energy into kinetic energy; a burning matchstick converts chemical energy into thermal and radiant energy. Our sun converts nuclear energy into thermal and radiant energy. A hydroelectric dam converts gravitational energy into electrical energy, while an electric motor converts electrical energy into kinetic energy.

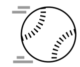
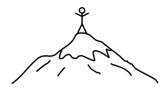
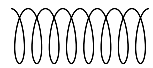
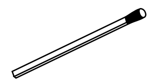
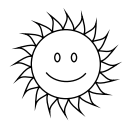
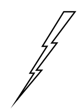
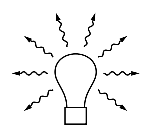
Type of energy	Physical manifestation	Example
Kinetic	Motion	
Gravitational	Height above some reference level	
Elastic	Stretch or compression	
Chemical	Molecules that can react and give off heat	
Nuclear	Nuclei that can react and give off heat	
Thermal	High temperature	
Electrical	Voltage and current	
Radiant	Light and other electromagnetic waves	

Figure 1.1. A list of the most important types of energy, with examples.

Energy conversions have been familiar to humans for thousands of years. Only over the last few centuries, however, did scientists gradually realize that during every energy conversion, they could account for the energy, unit by unit, in a quantitative way. If you carefully measure the amount of energy before and after some process, taking all forms of energy into account, you find that the *total* amount of energy never changes. Energy can be converted from one form to another, but it *cannot* be created, nor can it be destroyed. This principle is one of the deepest in all of science, and also one of the most useful. In scientific jargon, this principle is known as the **law of conservation of energy**, and also as the **first law of thermodynamics**.

In everyday life, "conservation of energy" has a completely different meaning, namely, using *less* of it. Please don't confuse this use of the word "conservation" with the more technical meaning in the previous paragraph. But if energy cannot be destroyed, what does it mean to "use" energy? The answer lies in the fact that some forms of energy are more useful than others. Our modern industrial society converts energy from more useful forms (mostly chemical energy) into less useful forms (dispersed thermal energy) at a tremendous rate. This is some cause for concern, because supplies of energy in useful forms may be limited, and because energy conversions often have unwanted side effects. "Conserving" energy, in the everyday sense of the word, simply means carrying out these conversions to a lesser extent.

Thermal energy is the least useful form of energy. Although it *can* be partially converted into other forms (as in an automobile engine where it is partially converted to kinetic energy), this conversion is never complete. Furthermore, thermal energy tends naturally to disperse over time, and once it is widely dispersed, it is effectively useless. These annoying properties of thermal energy are summarized in the **second law of thermodynamics**, a principle that is just as important as the principle of conservation of energy (the first law). The second law will be the subject of the second part of this course.

Exercise 1.1. Name a process or a device (other than those mentioned in the text above) that converts energy in each of the following ways:

- **(a)** from gravitational to kinetic;
- **(b)** from kinetic to thermal;
- **(c)** from thermal to kinetic;
- **(d)** from electrical to thermal;
- **(e)** from electrical to gravitational;
- **(f)** from chemical to gravitational;
- **(g)** from chemical to electrical;
- **(h)** from electrical to chemical;
- **(i)** from nuclear to electrical;
- **(j)** from kinetic to electrical;
- **(k)** from radiant to electrical.

Units of Energy

Just as distances can be measured in inches or meters or miles or microns or light-years, so also energy can be measured in many different units: joules, calories, British thermal units, kilowatt-hours, electron-volts, and quads, to name a few. Although life might be simpler if there weren't so many *different* energy units, each of these units came into use for excellent reasons, and every educated person needs to learn at least the most common energy units, and how to convert a quantity of energy from one unit of measure to another.

The official, internationally accepted energy unit for scientific work is the **joule**, abbreviated J. A joule is a rather small amount of energy, roughly equal to the kinetic energy of a very gently tossed baseball, or to the gravitational energy that you give to a baseball when you lift it by two feet (70 centimeters).

A more familiar energy unit is the **calorie** (cal). The original definition of the calorie was the amount of thermal energy required to raise the temperature of a gram of water by one degree Celsius. This amount of energy turns out to equal about 4.2 joules, and the calorie is now *defined* to equal precisely 4.186 joules. This is still a rather small amount of energy. The familiar "food calorie," used to measure chemical energy that our bodies can extract from food, is actually a **kilocalorie** (kcal), or 1000 calories—enough energy to raise the temperature of a *kilo*gram of water by one degree Celsius. In this course I'll always refer to food calories as "kilocalories," to avoid ambiguity.

As an example that is both vivid and useful (if not particularly nutritious), consider a typical jelly donut, which provides about 250 kilocalories. Since a kilocalorie is about 4000 joules, one jelly donut provides approximately one million (250×4000) joules, or one *mega*joule, of chemical energy. Some physicists go so far as to define a unit of energy called the **jelly donut** (JD), equal to exactly one megajoule (MJ). A typical American adult consumes the equivalent of about ten jelly donuts each day, or roughly 2500 kilocalories.

In the British system of units, the analogue of the kilocalorie is the **British thermal unit** (Btu), defined as the amount of thermal energy required to raise the temperature of one *pound* of water by one degree *Fahrenheit*. Since a pound is smaller than a kilogram and a degree Fahrenheit is smaller than a degree Celsius, a Btu is *smaller* than a kilocalorie—about one fourth the size, it turns out. This means that a Btu is approximately 1000 joules. This is still a rather small amount of energy compared to what's involved in heating or cooling a building or a large tank of water, so it's common (in the U.S.) to see thermal energies measured in millions of Btu's (MBtu). The natural gas that I use to heat my home is billed in these units; I currently pay about $6 per MBtu.

Electrical energy, meanwhile, is most often measured by the **kilowatt-hour** (kWh), a unit whose origin I'll explain in the next section. One kilowatt-hour equals exactly 3.6 million joules, which is approximately 860 kilocalories or 3400 Btu. For this amount of electrical energy I currently pay about seven cents.

Table 1.1 summarizes the conversions among these various energy units. I suggest that you memorize the *approximate* values of these conversion factors, to help develop your intuition for various amounts of energy. Although these energy units are the ones we'll use most frequently in this course, I'll occasionally introduce other units when they are convenient for specific applications.

$$1\ \text{kcal} = 4186\ \text{J} = 3.97\ \text{Btu} = 0.00116\ \text{kWh}$$
$$1\ \text{Btu} = 1054\ \text{J} = 0.252\ \text{kcal} = 0.000293\ \text{kWh}$$
$$1\ \text{kWh} = 3,600,000\ \text{J} = 860\ \text{kcal} = 3413\ \text{Btu}$$

Table 1.1. Conversions among the most commonly used energy units. For most purposes, you can round these numbers off; for instance, 1 kcal $\approx$ 4000 J $\approx$ 4 Btu $\approx$ 0.001 kWh.

Often we're given a quantity of energy in one unit of measure, but we need to express it in terms of some other unit. For example, the chemical energy released by burning a gallon of gasoline is approximately 124,000 Btu; what is this in kilocalories? To answer this question we need to use one of the conversion factors in Table 1.2—namely, 1 kcal = 3.97 Btu. But should we multiply or divide 124,000 by 3.97? A sure-fire way to keep it straight is as follows. Note that since 1 kcal = 3.97 Btu, we can write

$$\frac{1 \text{ kcal}}{3.97 \text{ Btu}} = 1. \tag{1.1}$$

Multiplying a number by 1 doesn't change it, so we can then write

$$\begin{aligned} 124,000 \text{ Btu} &= (124,000 \text{ Btu}) \times (1) = (124,000 \cancel{\text{Btu}}) \times \left(\frac{1 \text{ kcal}}{3.97 \cancel{\text{Btu}}}\right) \\ &= 31,234 \text{ kcal} \approx 31,000 \text{ kcal}. \end{aligned} \tag{1.2}$$

Notice that I've canceled out the unit Btu, just as if it were an algebraic symbol; this leaves us with the desired unit, kcal. More generally, the most error-proof way to convert units is simply to multiply by 1 in the form of a ratio that expresses the relevant unit relation.

Of course, you could just as well invert equation 1.1, to obtain instead

$$\begin{aligned} 124,000 \text{ Btu} &= (124,000 \text{ Btu}) \times (1) = (124,000 \text{ Btu}) \times \left(\frac{3.97 \text{ Btu}}{1 \text{ kcal}}\right) \\ &= 492,000 \text{ Btu}^2/\text{kcal}. \end{aligned} \tag{1.3}$$

Now, however, the unit Btu appears twice in the numerator, so it doesn't cancel out as before. The result is still *correct*, but it's not useful to us, since we're left with an entirely new and bewildering unit of energy, the "Btu squared per kilocalorie." (Whenever a unit conversion goes awry like this, all you have to do is go back and invert the conversion factor.)

This same method can be used for any other unit conversion, no matter how complicated. For example, given that there are 3600 seconds in an hour and 1609 meters in a mile, we can derive the conversion factor between miles per hour (a common unit of speed in the U.S.) and meters per second (the official scientific unit of speed):

$$\begin{aligned} 1\,\frac{\text{meter}}{\text{second}} &= \left(1\,\frac{\text{meter}}{\text{second}}\right)(1)(1) = \left(1\,\frac{\cancel{\text{meter}}}{\cancel{\text{second}}}\right)\left(\frac{1 \text{ mile}}{1609 \cancel{\text{meters}}}\right)\left(\frac{3600 \cancel{\text{seconds}}}{1 \text{ hour}}\right) \\ &= 2.24\,\frac{\text{miles}}{\text{hour}} = 2.24 \text{ mph}. \end{aligned} \tag{1.4}$$

This example also shows how the simple units of distance and time can be combined into a compound unit (meters/second or miles/hour) to express speed. Many other combinations are also possible. For instance, we commonly express surface areas in square feet (ft^2) or square meters (m^2). My house happens to occupy an area of

936 ft^2; to convert this number to square meters, I can just multiply twice by the appropriate conversion factor:

$$936\ \text{ft}^2 = (936\ \text{ft}^2)(1)^2 = (936\ \cancel{\text{ft}^2})\left(\frac{1\ \text{m}}{3.28\ \cancel{\text{ft}}}\right)^2 = 87\ \text{m}^2. \tag{1.5}$$

(This number can be used to estimate how much solar radiant energy strikes my roof each day, as we'll see later.)

Exercise 1.2. One jelly donut (JD) of energy is about 250 kilocalories or one megajoule. What is this in Btu's? In kilowatt-hours? (Please round off your answers appropriately.)

Exercise 1.3. The speed limit on the urban portions of Interstate 15 is 65 mph. What is this in meters per second?

Exercise 1.4. Given that there are 100 centimeters in a meter, how many cubic centimeters are in a cubic meter?

Exercise 1.5. The average American passenger car or light truck can drive about 20 miles on a gallon of gasoline: we say that its "fuel economy" is 20 miles per gallon. In the rest of the world, fuel economy would be expressed in kilometers per liter. Given that there are 1.6 kilometers in a mile and 3.8 liters in a gallon (approximately), express the fuel economy of the average American passenger vehicle in kilometers per liter.

Exercise 1.6. Compute the retail cost of one jelly donut (JD) of energy, if it is in each of the following forms: (a) gasoline; (b) natural gas; (c) electricity; (d) an actual jelly donut. (If possible, consult your utility bills to determine the current cost of natural gas and electricity. If this is impractical, use the costs that I quoted above from my bills.)

Power: The Rate of Energy Conversion

Often we're interested not just in the *total* amount of energy converted in some process, but also in the *rate* at which that energy is converted. A person consumes 2500 kilocalories *per day*; a furnace puts out 100,000 Btu *per hour*; a power plant generates one billion joules *per second*. To calculate the rate of energy conversion, all you have to do is divide the amount of energy converted by the amount of time it took. Scientists use the term **power** for this ratio:

$$\text{power} = \frac{\text{energy}}{\text{time}} \qquad \text{(definition of power)}. \tag{1.6}$$

For instance, if in climbing a flight of stairs you gain 2000 joules of gravitational energy over a period of 5 seconds, we would say that the power output of your legs is

$$\text{power} = \frac{2000\ \text{J}}{5\ \text{s}} = 400\ \text{J/s}. \tag{1.7}$$

(Since you are not 100% efficient at converting chemical energy into gravitational energy, the rate at which your muscles *consume* chemical energy is actually greater;

the rest of the chemical energy gets converted to thermal energy, as you've probably noticed while exercising.)

The joule per second (J/s) is the official scientific unit of power, and has its own name: the **watt** (W). Thus, we could just as well say that the power output of your legs in climbing the stairs is 400 watts. Since a watt is a rather small amount of power (very roughly the rate at which a flashlight bulb converts electrical energy into thermal and radiant energy), we often attach to it the prefixes kilo (for a thousand), mega (for a million), or giga (for a billion). A typical American home consumes electrical energy at an average rate of about a kilowatt (1 kW = 1000 J/s = 10^3 J/s); a large truck consumes chemical energy (diesel fuel) at a rate of about a megawatt (1 MW = 1,000,000 J/s = 10^6 J/s); and a large power plant generates electricity at a rate of about a gigawatt (1 GW = 1,000,000,000 J/s = 10^9 J/s).

Another unit of power that you've probably heard of is the **horsepower**, approximately the power output of a draft horse working steadily. Since all horses are not created equal, today the horsepower is *defined* as exactly 746 watts; whether your horse can actually produce one horsepower is your own problem. Other units of power can be created by combining any unit of energy with any unit of time, as in Btu/hr (used for heating and cooling appliances) or kcal/day (convenient for talking about the human diet).

If you know the power involved in some process and want to calculate the total energy, you have to multiply by the time elapsed:

$$\text{energy} = (\text{power}) \times (\text{time}). \tag{1.8}$$

This is just an algebraic rearrangement of equation 1.6. For instance, if you leave a 1000-watt electric heater running all day long, its total energy consumption is

$$\text{energy} = (1000\ \text{J}/\cancel{\text{s}}) \times (24\ \cancel{\text{hours}}) \times \left(\frac{3600\ \cancel{\text{s}}}{1\ \cancel{\text{hr}}}\right) = 86,400,000\ \text{J}, \tag{1.9}$$

more than 86 megajoules. If you convert this number to kilowatt-hours, you'll find that it's exactly 24 kWh. This is because the kilowatt-hour is *defined* to equal a kilowatt multiplied by an hour:

$$1\ \text{kWh} = (1\ \text{kilowatt}) \times (1\ \text{hour}) = (1000\ \text{J}/\cancel{\text{s}}) \times (3600\ \cancel{\text{s}}) = 3,600,000\ \text{J}. \tag{1.10}$$

Thus, if we want the answer in kilowatt-hours (which is more useful in calculating the cost of the electricity), we can simplify the calculation in equation 1.9 as follows:

$$\text{energy} = (1\ \text{kW}) \times (24\ \text{hours}) = 24\ \text{kWh}. \tag{1.11}$$

Just remember that the kilowatt-hour is a unit of *energy*, not power, while the kilowatt (or megawatt, etc.) is a unit of *power*, not energy. (Newspaper writers seem to get this wrong about as often as they get it right, indicating that they're just guessing randomly. Now you know better!)

Exercise 1.7. Suppose that your car consumes a gallon of gasoline in half an hour. What is its rate of chemical energy consumption, in watts and in horsepower? (Note that the engine's rate of useful power output is less, because much of the energy is lost as thermal energy, out the tailpipe.)

Exercise 1.8. Knowing the caloric content of a typical person's diet, calculate the average rate at which a person consumes chemical energy (converting it mostly into thermal energy). Express the answer in watts and in horsepower.

Exercise 1.9. Suppose that you leave a 60-watt light bulb burning 24 hours a day, 365 days a year. How much electrical energy does it use in a year? Express your answer in kilowatt-hours. If electricity costs 7 cents per kWh, what is the annual cost of burning this light (just for the electricity, not including replacement bulbs)?

Exercise 1.10. The maximum mechanical power output of the human body over extended time periods is about half a horsepower. Consider a Tour-de-France rider, who maintains this power level for about six hours during a day's ride. What is the rider's total mechanical energy output during the ride, expressed in units of jelly donuts? ("Mechanical" energy in this context means energy that goes into pushing the pedals. The rider's total energy output (and hence, required energy input) is actually about four times as large, because the body is only about 25% efficient at converting chemical energy into mechanical energy. The other 75% of the energy is "wasted" as thermal energy.)

Exercise 1.11. A news article states that California's utility companies have occasionally paid as much as $2000 per megawatt for electricity. What's wrong with this statement?

Exercise 1.12. A salesman tells you that a particular air conditioner is rated at 5000 Btu. What's wrong with this statement?