If you glance back at Figures 6.12 and 6.14, you get the impression that the energy that goes into many processes eventually turns into thermal energy. This tendency of nonthermal forms of energy to end up as thermal energy is an important general feature of the universe, known as the second law of thermodynamics. It is our focus in this chapter.

As you saw in Chapter 6, the big breakthrough in understanding energy was the discovery that heat (thermal energy) is actually a form of energy, in other words that heat can do work and can be created by doing work, just as can other forms of energy. This breakthrough established the validity of the law of conservation of energy even in processes involving thermal energy, and, in fact, in every known natural process. Because of the central role of thermal energy in understanding the general principles of energy, the study of energy is called thermodynamics, and the law of conservation of energy is often called the first law of thermodynamics.* These laws of thermodynamics have no known exceptions and are among the most general scientific principles known.

There are three different ways of stating the second law. In its most straightforward form, it is a familiar observation about thermal energy flow (Section 7.1). Like many everyday observations, this one has profound consequences. Section 7.2 discusses one of these, namely, another form of the second law that highlights the special nature of thermal energy. Unlike other energy forms, there is a restriction on the transformations of thermal energy: It can be transformed into other forms only with limited efficiency. This leads to discussion of a device that is central to society's use of energy: the heat engine (Sections 7.2 and 7.3). Section 7.4 presents yet another way of stating the second law, known as the law of increasing entropy. This law provides insight into some fundamental philosophical and cultural issues, including the direction of time, the ultimate fate of the universe, and why there is a second law of thermodynamics. Sections 7.5 and 7.6 apply the laws of thermodynamics to our continuing study of the physics and social implications of a significant heat engine: the automobile. Section 7.7 looks at another significant heat engine: the steam-electric power plant. Because these topics bring up the question of the use and depletion of energy resources, it is

*Textbooks usually state the first law of thermodynamics in a form that looks different from the law of conservation of energy. Nevertheless, the two ideas are logically equivalent to each other.
natural at this point to discuss exponential growth and its implications for resource depletion (Section 7.8).

7.1 HEATING

Touch a piece of ice (Figure 7.1). Energywise, what happens? Your hand gets cooler, and the ice begins to melt. So thermal energy must have flowed from your hand to the ice. Now touch a hot cup of coffee (Figure 7.2). Your hand gets warmer while the coffee cools, so thermal energy must have flowed from the cup to your hand. Notice that in each case, thermal energy flowed from the high-temperature object to the low-temperature object. There is a general principle operating here, a principle that you experience whenever you touch an object that feels hot or cold: Thermal energy flows spontaneously from hot to cold. Any such flow of thermal energy from a high to a low temperature is called heating.

Heating has a one-way nature: It flows "downhill" from a high to a low temperature. It won't flow spontaneously (without external help) "uphill" from a low to a high temperature. Like a lot of simple ideas, this one-wayness of heating has profound consequences. It is one way of stating the second law of thermodynamics:

THE SECOND LAW OF THERMODYNAMICS, STATED AS THE LAW OF HEATING
Thermal energy flows spontaneously (without external assistance) from a higher-temperature object to a lower-temperature object. It will not spontaneously flow the other way.

Now we need to be more quantitative about temperature. Temperature is a quantitative measure of warmth. We can measure temperature by using any material that expands as it warms and contracts as it cools. Most materials do this. Such an expansion and contraction can be used as the basis for a temperature-measuring device, or thermometer. One choice is liquid mercury, which expands inside a glass tube. The standard (metric) temperature unit is the degree Celsius (°C). The Celsius scale assigns 0°C and 100°C to the freezing and boiling points of water. The United States still uses the Fahrenheit scale, related to the Celsius scale as shown in Figure 7.3.

Temperature and thermal energy are related but different. For instance, a cool lake contains much more thermal energy than does a hot cup of coffee, even though the lake has a lower temperature, because the lake is so much larger.

**Dialogue 1** To develop a feel for Celsius temperatures, answer the following questions in °C. What is the approximate temperature of a nice day? Of a hot day? What temperatures are below freezing? Above boiling?

1. 20–25°C, 35–40°C, below 0°C, above 100°C.
7.2 Heat Engines: Using Thermal Energy to Do Work

Drop a book on the floor. Slide it across the table. Smack it with your hand. Imagine tearing out a page and burning it up. (Books come in for a certain amount of rough treatment in physics courses.) Consider the energy transformations during these processes: Thermal energy is created during each one! It’s hard to think of a physical process that doesn’t create at least a little thermal energy. It is easy—almost inevitable—to create thermal energy.

But processes that consume thermal energy as the input and then convert it to other forms are less common. Can you think of any?

—Time out, for thinking.

One example is the automobile engine, which uses thermal energy to do work. Any device that uses thermal energy to do work is called a heat engine.

One significant feature of an automobile engine is that, in addition to doing work, it ejects a lot of thermal energy. The automobile’s radiator ejects excess thermal energy, and its tailpipe exhausts residual hot gases. So not all the thermal energy input is actually used to do work. This turns out to be a general feature of every heat engine. A heat engine’s thermal energy output is called its exhaust.

So the energy transformation for any heat engine is

\[
\text{ThermE (input)} \rightarrow \text{Work (which could then produce any form of energy)} + \text{ThermE (exhaust)}
\]

See Figure 7.4.

Because of the social significance of heat engines, we should quantify their performance. Recall from Chapter 6 that the energy efficiency of any device is its useful energy output divided by the total energy input, often expressed as a percentage. Thus the energy efficiency of any heat engine is its work output divided by the thermal energy put into it:

\[
\text{energy efficiency} = \frac{\text{work output}}{\text{thermal energy input}}
\]

The notion that heat engines always have an exhaust can then be stated very simply: Heat engines are always less than 100% efficient.

This special feature of thermal energy—that you can entirely create it but you can’t entirely consume it—has been found to be true every time we have checked. It is, in other words, a fundamental principle of nature. But as we will see, it turns out not to be another new principle of nature. It has a one-way quality about it that is reminiscent of the law of heating. Perhaps it is not surprising then that it turns out to be the second law of thermodynamics, only put into words that are different from our previous statement. We call it:
THE SECOND LAW OF THERMODYNAMICS, STATED AS THE LAW OF HEAT ENGINES

Any process that uses thermal energy as the input to do work must also have a thermal energy output or exhaust. In other words, heat engines are always less than 100% efficient.

HOW DO WE KNOW?

Why do we believe the law of heat engines? Rather than appealing directly to experiment, we offer a theoretical argument based on the law of heating, which is in turn based on experiment. It is a type of argument that logicians call an argument by contradiction or a reduction to an absurdity.

Let’s temporarily suppose that (in violation of the law of heat engines) there is a heat engine that can convert thermal energy entirely to work. We could then use that heat engine to extract thermal energy from, say, a pot of warm water and convert this energy entirely to work. This work could produce thermal energy (by friction, for example) in some hotter system, such as a pot of hotter water. The net result would be to transfer thermal energy “uphill,” from a lower to a higher temperature, without any other change taking place. But this is absurd—it’s exactly what the law of heating says we cannot do. In other words, any violation of the law of heat engines implies that the law of heating is also violated. But we know directly from many experimental observations that the law of heating is not violated. So it follows that the law of heat engines cannot be violated either.

Following the above argument, it should come as no surprise that the flow of thermal energy from a high to a low temperature is essential to heat engines. In fact, a heat engine may be described as a device that uses the natural hot-to-cold flow of thermal energy, by shunting aside some of the flowing thermal energy to do work (Figure 7.5). Keep in mind that Figure 7.5 is only a graphical way of showing the energy flow and is not a picture of an actual heat engine.

Since heat engines are driven by the flow of thermal energy from hot to cold, you must have a difference in temperatures before you can have a heat engine. You cannot turn thermal energy into work if you have only a single temperature to work with. The ocean, for example, contains a lot of thermal energy, but you cannot use it to do work unless you have a colder system for the ocean’s thermal energy to flow into.* Heat engines always operate between two systems with different temperatures, as Figure 7.5 shows.

How efficient can the very best heat engine be? It’s an important question, because most of the world’s primary energy (energy that comes directly from nature) passes through heat engines. In the United States, fully 60% of the primary energy consumed each year passes through either a transportation vehicle or a steam-electric power plant. Both of these devices are heat engines, subject to the second law.

*This means that temperature differences between different depths of ocean water could be used to run a heat engine.
Since a heat engine operates because of the ability of thermal energy to flow from hot to cold, we expect its efficiency to be influenced by both its hot input temperature (the temperature at which thermal energy is put into the engine) and its cooler exhaust temperature. Since temperature differences drive heat engines, we expect a higher efficiency for larger temperature differences between the input and the exhaust. Nineteenth-century physicists found a quantitative formula that predicts the best or ideal efficiency of a heat engine operating at any predetermined input and exhaust temperatures.* As examples, Table 7.1 lists the predicted ideal efficiencies for several specific types of heat engines, along with the actual efficiencies obtained by these heat engines in practice.

Table 7.1 shows how important the second law is to society, as even the ideal efficiencies of these heat engines are 60% or less. Friction, air resistance, and other nonideal processes reduce this even further. Less than half the natural energy resources used in these heat engines are employed to do work. This doesn’t necessarily mean, however, that all of the remainder is wasted, because the exhausted thermal energy might be warm enough to be used directly for heating. Indeed, many countries’ steam-electric power plants make use of such cogeneration of both electricity and useful thermal energy.

Table 7.1 shows the importance of “burning hot” and “exhausting cool.” For example, the fossil, nuclear, and solar generating plants have progressively lower input temperatures, but they all exhaust to cooling water that is at about 40°C. As you can see, the efficiency declines as the difference between \( T_{in} \) and \( T_{ex} \) declines.

Ocean-thermal generation of electric power is a plan to use some of the ocean’s thermal energy by exploiting temperature differences at different ocean depths. In the tropics, the ocean’s temperature drops rapidly from 25°C at the surface to 5°C at 300 m beneath the surface. This small temperature difference could be used to run a heat engine with an efficiency of less than 7%. Because

| TABLE 7.1 |
| Heat engine efficiencies. Typical input and exhaust temperatures, ideal (best possible) efficiencies, and actual efficiencies. |

<table>
<thead>
<tr>
<th>Engine type</th>
<th>( T_{in} ) (°C)</th>
<th>( T_{ex} ) (°C)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline automobile/truck</td>
<td>400</td>
<td>25</td>
<td>55 10–15</td>
</tr>
<tr>
<td>Diesel auto/truck/locomotive</td>
<td>500</td>
<td>25</td>
<td>60 15–20</td>
</tr>
<tr>
<td>Steam locomotive</td>
<td>180</td>
<td>100</td>
<td>18 10</td>
</tr>
<tr>
<td>Steam-electric power plants</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fossil fuel</td>
<td>550</td>
<td>40</td>
<td>60 40</td>
</tr>
<tr>
<td>Nuclear powered</td>
<td>350</td>
<td>40</td>
<td>50 35</td>
</tr>
<tr>
<td>Solar powered</td>
<td>225</td>
<td>40</td>
<td>38 30</td>
</tr>
<tr>
<td>Ocean-thermal</td>
<td>25</td>
<td>5</td>
<td>7  ??</td>
</tr>
</tbody>
</table>

*The formula is efficiency = \((T_{in} - T_{ex})/T_{in}\). In this formula, the temperatures must be measured in degrees Kelvin (K), a new temperature scale. The temperature in K is found by adding 273 to the temperature in °C. 0 K (or −273°C) is known as absolute zero, because it is the lowest possible temperature—the temperature at which all microscopic motion is at its absolute minimum.
the primary energy resource would be solar energy falling on the ocean, the low efficiency would be of little concern. But because the intake point for cool water must be 300 m below the ocean's surface, the engineering problems would be formidable.

**Dialogue 2**  
(a) Assume that the energy flows in Figure 7.5 are proportional to the width of each pipe. Estimate this engine's efficiency. (b) Suppose this engine consumes 400 J of thermal energy and converts 300 J of this to exhaust. Find the engine's efficiency.

**Dialogue 3**  
A typical large coal-fired electric generating plant burns about 1 tonne (1000 kg) of coal every 10 seconds. According to Table 7.1, how much of the tonne actually goes into producing electric energy? How much goes into exhaust?

**Dialogue 4**  
A coal-burning steam locomotive heats steam to 180°C and exhausts it at 100°C. During 1 s of operation, it consumes 500 million J of energy from the burning coal. According to Table 7.1, how much work can be obtained from this locomotive during 1 s of operation under ideal conditions (no friction or other imperfections)? How much work can be obtained under actual conditions?

### 7.3 Energy Quality: Things Run Down

The second law tells us that thermal energy is less useful than are other types of energy, because unlike the other forms, not all its energy can be used to do work. In this sense, thermal energy is lower-quality energy. A moving bullet or a raised rock can convert its kinetic or gravitational energy entirely to work, but thermal energy can be only partially used to do work. So whenever you transform other energy forms into thermal energy—say by friction or combustion—you reduce the energy's quality.

So there is an irreversibility about any process that creates thermal energy. Once a system creates thermal energy, that system will never by itself (spontaneously) be able to return to its previous condition. To return, it would have to convert spontaneously all the created thermal energy to its original form, and the second law prohibits this. The system can return to its initial state only with outside help.

A good example is a rock swinging back and forth on a string tied to a hook (Figure 7.6). Air resistance and friction (between the string and the hook) gradually bring the rock to rest. Although the complete system (rock, string, hook, and surrounding air) loses no energy, it can't return to its initial condition because thermal energy is created, and this cannot be entirely reconverted to kinetic or gravitational energy. Something is permanently lost when systems run down like this, but it cannot be energy because energy is conserved. Instead, en-

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2. (a) Something like 30%, judging from the widths of the "pipes." (b) Work = 400 - 300 = 100 J. Efficiency = 100/400 = 0.25 = 25%.

3. 40% of 1000 kg is 400 kg; the remaining 600 kg goes into exhaust.

4. Ideal efficiency = 0.18, 0.18 × 500 × 10^6 J = 90 × 10^6 J. Actual efficiency = 0.10, 0.10 × 500 × 10^6 J = 50 × 10^6 J.
Energy quality is lost. The system’s energy gradually decreases in quality until all of it has turned into thermal energy at a temperature only slightly warmer than the surroundings. Now the original energy is almost entirely useless.

When we use Earth’s energy resources, we don’t use up energy. Instead, we degrade energy from highly useful forms such as the chemical energy of oil to less useful forms such as thermal energy.

One of the two great laws of energy says that the quantity of energy is conserved, and the other says that the quality of energy runs down. You can’t get ahead, and you can’t even break even.

### 7.4 The Law of Entropy: Why You Can’t Break Even

You have seen the second law stated in two different ways. Now we’ll look at yet a third way, which puts it in terms of nature’s microscopic behavior.

Suppose that a box of hot gas and a box of cold gas are put into contact. The second law says that the hot box will heat the cold one and will continue heating it until there is no longer a temperature difference between the boxes.

Figure 7.7 shows this process from the microscopic point of view. Microscopically, the difference between the hot gas and the cold gas is that the hot box’s molecules are moving at higher speeds on the average (note that they aren’t all moving at the same speed—they have various speeds), while the cold box’s molecules are moving at lower speeds on the average; Figure 7.7a shows just a few of the molecules in the hot gas on the left and in the cold gas on the right. The exchange of thermal energy from the hot gas to the cold gas causes the molecules of the hot gas to slow down and the molecules of the cold gas to speed up (Figure 7.7b) until both gases come to some intermediate temperature. Once the two boxes have reached the same temperature, we no longer have the separation of speeds with which we started. We can no longer say, with any

![Microscopic view showing just a few of the molecules in a box of hot gas and a box of cold gas that are put into contact. The final situation shows greater disorganization than the initial situation, because the faster molecules are no longer separated from the slower molecules.](image)

**FIGURE 7.7**

*Microscopic view showing just a few of the molecules in a box of hot gas and a box of cold gas that are put into contact. The final situation shows greater disorganization than the initial situation, because the faster molecules are no longer separated from the slower molecules.*
confidence, that we can find a fast molecule by reaching into the left-hand box or a slow molecule by reaching into the right-hand box. Instead, the molecules in both boxes have come to an intermediate average speed, with slower and faster molecules mixed together in both boxes.* From the microscopic point of view, the system is less organized. Microscopic disorganization has increased.

This turns out to be the general situation, no matter whether the materials are gases or anything else. When thermal energy flows from hot to cold, microscopic disorganization always increases. In fact, this idea—that microscopic disorganization must increase—is equivalent to the fact that thermal energy flows from a high to a low temperature. In other words, this idea is another way of stating the second law.

Physicists have found a quantitative measure of the disorganization at the microscopic level of any system. It is called entropy. We don’t need to delve into the precise definition of entropy here. Suffice it to say that it can be specified by measurements of temperature and thermal energy.

So we have yet another way of stating the second law:

**THE SECOND LAW OF THERMODYNAMICS, STATED AS THE LAW OF INCREASING ENTROPY**
The total entropy of all the participants in any physical process must either increase or remain unchanged; it cannot decrease.

The law of increasing entropy is similar to the law of conservation of energy. Both place restrictions on natural processes: The total energy of all the participants in any process must remain unchanged, and the total entropy must not decrease.

But unlike the law of energy, the law of entropy predicts that most processes are irreversible—they cannot proceed in the opposite direction. Processes must go in the direction of increasing, not decreasing, entropy. In fact, except for a very subtle effect at the subatomic level,¹ the second law is the only principle of physics that distinguishes between a forward and a backward direction of time. If it weren’t for the second law, everything could just as well run backward. For example, a book resting on a table could spontaneously leap into the air by converting some its thermal energy into kinetic and gravitational energy. This is the reverse of dropping a book onto a table. It might appear to violate such principles as Newton’s law of motion, but if viewed at the microscopic level there is no violation: It is possible, although highly improbable, for the randomly moving molecules in the book to all just happen to be moving upward at the same instant, with sufficient speed to cause the book to leap from the table as though

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*If the boxes contain different kinds of gases, O₂ in one box and N₂ in the other, for example, then the average kinetic energies, rather than the average speeds, of the individual molecules of the two gases become equal when a common intermediate temperature is attained.

¹The effect involves the decay (or disintegration) of a particle known as the K-meson. Physicists James Cronin and Val Fitch discovered in 1964 that K-mesons distinguish between forward and backward in time. It is not known whether this subatomic physics discovery is in any way related to the second law or to our sense of a forward direction in time, although it does appear to be responsible for the fact that the big bang origin of the universe created mostly matter rather than antimatter. One member of the 1980 committee that awarded Cronin and Fitch their Nobel Prize remarked, “It would take a new Einstein to say what it means.”
the table had thrown the book upward. Similarly, water could run uphill. Thermal energy could flow from cold to hot. And people could grow younger instead of older. Perhaps you have seen a movie run backwards. Despite the odd appearance of the events in such a movie, the only law of physics that would be violated if these events actually occurred in real time is the second law of thermodynamics!

The law of entropy shows us why there is a limit on the possible efficiency of even the most perfectly constructed heat engine. When a heat engine uses some of its thermal energy to do work, it turns disorganized energy into organized energy. If there were no exhaust, this use of thermal energy to do work would violate the law of increasing entropy. The exhaust prevents this violation, because we saw in Figure 7.7 that disorganization increases when thermal energy flows from hot to cold. In a heat engine, the increase in disorganization caused by the thermal energy flow from hot to cold must at least balance the increase in organization caused by the conversion of some of the thermal energy into work. Overall, there must be a net increase (or, in the case of a perfectly constructed heat engine, zero increase) in disorganization. So there must be an exhaust.

The law of increasing entropy suggests a deeper reason behind the second law. Increased disorganization is common in everyday life. For example, suppose that you have a partially organized deck of cards, perhaps with all the spades collected together. If you now shuffle the deck, you will almost certainly disorganize the deck further. It is possible, but improbable, that the shuffling will further organize the cards, perhaps by leaving the spades together and, luckily, collecting the hearts together also. But the deck of cards is much more likely to evolve toward a more disorganized state, simply because there are so many more ways to disorganize the deck than there are ways to organize it. As you know whenever you clean your house, it is easy to disorganize things, but it takes effort—or a lot of luck—to organize them.

Thus the second law arises for simple statistical reasons. Like a deck of cards, molecular systems are much more likely to evolve toward greater disorganization than toward greater organization, simply because there are many more ways for a molecular system to become disorganized than to become organized. It is highly likely (in fact, overwhelmingly likely) that such systems will become more disorganized.

The second law leads to some interesting speculation about the possible long-term fate of the universe. Unless there are other universes of which we are unaware, our universe would appear to be an isolated system—a system to which one can apply the laws of thermodynamics. If one applies the second law to the universe as a whole, one concludes that the natural evolution of the universe must be toward states of greater and greater disorganization. The long-term fate of the universe would then have to be a state of maximum disorganization, in which no further macroscopic developments would be possible (more precisely, such developments would be highly unlikely).

Such a maximum entropy state would be pretty boring. Among other things, all the stars would have burned out and no new ones could form because all possible nuclear reactions would have run their course. Life could not exist because of the lack of sunlike stars. A more fundamental reason why life could not exist is that living organisms represent a highly organized state of matter—just the kind of low-entropy state that could not exist once the universe had evolved to its maximum-entropy state. This long-term fate of the universe has been termed
the heat death of the universe. It’s not exactly the world’s most pressing issue, since it is hundreds of billions of years in the future, but it raises interesting and perhaps troubling philosophical questions. I hasten to add that there is a large speculative element in the notion of a universal heat death, because we are not necessarily justified in applying the laws of thermodynamics to the entire universe or to very long times. It is always risky to assume that the principles of physics as we now understand them are so precisely correct that they can be applied to the universe as a whole, or to all future time.

Biological systems provide interesting examples. For example, a growing leaf manufactures complex glucose molecules out of simple CO₂ and H₂O molecules. Glucose is highly organized when compared with the randomly moving CO₂ and H₂O that goes into its formation. The leaf must create this organization. How does it manage to produce this decrease in entropy, in apparent violation of the second law?

The answer is that the leaf had help. The second law says that the total entropy of all the participants in any process cannot decrease. In the growth of a leaf, the other vital participant is the sun. Solar radiation has a temperature, the 5500°C surface temperature of the sun. When this radiation is absorbed by a leaf, only about 2% of the energy is converted to chemical energy. The remaining solar energy is reradiated out into space, at the 25°C temperature of the leaf. So most of the solar energy flows from 5500°C to 25°C, and the large entropy increase of this thermal energy flow allows the remaining solar energy to be organized into low-entropy chemical energy (Figure 7.8). Solar radiation organizes the leaf despite (but not in violation of) the second law. Solar radiation is both the energizer and the organizer of all life on Earth.

Creationism, the belief that the various biological species (and especially humans) originated from specific acts of instantaneous creation rather than by the natural process of biological evolution, argues that biological evolution is impossible because it violates the second law. It is an idea that seems plausible at first glance. After all, it does seem paradoxical that life on Earth could have evolved on its own from simple single-celled structures into the much more organized plants and animals of today. It seems overly lucky, and it seems to violate the second law’s demand that disorganization should always increase.

But like a leaf, biological evolution had help from the sun. The increase in entropy that occurs when sunlight is absorbed and reradiated by Earth is much more than adequate to compensate for the decrease that occurs when plants evolve into new organisms. And animals, which do not use solar energy directly, reduce their entropy by eating highly organized food—another form of outside help. Biological evolution is fully consistent with the second law. Over billions of years, Earth has evolved toward greater organization at the cost of a much greater disorganization of the solar radiation that has passed through biological systems.

Your brain is one result of this long evolution toward greater organization. As an information-storage device, the human brain is the most highly organized form of matter on Earth.* It is surely the most organized form of matter within some 4 × 10¹⁳ km from Earth—the distance to the nearest star beyond the sun—and perhaps within the entire Milky Way galaxy (see Chapter 12). It is remarkable that, in the human brain, nature has finally created a self-aware collection

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*Carl Sagan makes this point in The Dragons of Eden (Random House, New York, 1977), in which he estimates the information content of the brain’s neurons and compares it with computers, with other animal brains, and with the information content of genetic material.
of molecules, molecules so well organized that they are capable of knowing that they are a collection of molecules! Nature has spent billions of years of evolution getting to this point. So take good care of yourself and of all of us.

### 7.5 THE AUTOMOBILE

Few technologies shape our culture as strongly as the automobile. It brings great freedom while affecting our quality of life, family structure, self-perceptions, physical environment, health, work, community structure, resource use, economy, and even issues of war and peace. We cannot go into all these far-flung issues, but as part of our science-and-society theme, we will look at the automobile's role in energy-related matters.

Transportation consumes much of the energy used by the United States (Figure 7.9) and most of the nation's oil (Figure 7.10). Most of this is used by cars and trucks (Figure 7.11).

#### Making Estimates

Calorimetry experiments show that upon combustion, 1 gallon (3.8 liters) of gasoline releases (converts to thermal energy) about 130 million joules of energy. Use this figure to estimate the rate, in watts, at which a typical car consumes chemical energy while moving at highway speeds without acceleration. 

**Hints:** Typical gasoline consumption is 25 miles/gallon (10 kilometers/liter), and highway speeds are about 50 mi/hr (80 km/hr).

**Solution** During 1 hour at 50 mi/hr, a car travels 50 miles and so consumes 2 gallons. Since 1 gallon contains $1.3 \times 10^8$ J, the chemical energy in 2 gallons is $2.6 \times 10^8$ J. This is consumed in 1 hour. Since there are 3600 $(3.6 \times 10^3)$ seconds in 1 hour, the chemical energy consumed per second is

$$2.6 \times 10^8 \text{ J}/3.6 \times 10^3 \text{ s} = 0.7 \times 10^5 \text{ J/s} = 70,000 \text{ J/s}$$

or 70,000 watts or 70 kW.

The 70 kW consumed by a typical car is equivalent to the electric power going into 700 100-W bulbs burning the entire time the car is moving. As another comparison, the average rate at which a typical U.S. household consumes electric energy is about 1 kW, so while a car is moving, its energy use is equivalent to that of 70 households! If the car is accelerating, all of these figures should be multiplied by about 5.

Most transportation energy goes into heat engines, where it first burns to produce thermal energy and then is partially transformed into useful work. Cars and trucks are powered by **internal combustion** engines. Heat engines of this type burn a fuel–air mixture. The mixture's high combustion temperature gives it a high pressure, which enables the hot gases to push strongly on a piston, a movable metal plate connected to a rod (Figure 7.12). The piston does the work...
that turns the drive wheels. Combustion is internal because the combustion occurs directly inside the gases that do the work, in contrast with external combustion, which occurs in a fuel that then provides thermal energy to a second substance, such as steam, that does the actual work.

The most convenient and abundant automobile fuel is gasoline, a form of petroleum. But there are many other possibilities. As gasoline's pollution problems loom larger and as petroleum's availability declines, other, less-polluting fuels may become more popular. Table 7.2 (see also Figures 7.13 through 7.16) lists and describes possible automotive fuels.

Figure 7.17 shows the energy transformations in a typical automobile. On the average, 1 kW is lost to evaporation. It isn't really lost, as energy is never lost. But 1 kW of hydrocarbons goes into the atmosphere where its chemical energy essentially cannot be recovered and where it contributes to chemical pollution. The remaining 69 kW go to the engine, which produces about 17 kW of work and exhausts the remaining 52 kW as thermal energy and unused chemical energy.

About half of the exhaust energy is removed by the car's radiator, and the other half goes out through the exhaust pipe as polluting gases. Gasoline is a hydrocarbon, made of hydrogen (H) and carbon (C) atoms. Both the hydrogen and the carbon combust with oxygen from the atmosphere, so the exhaust gases are mostly CO₂ and H₂O. Although neither one is toxic (poisonous to humans), CO₂ contributes to environmentally harmful global warming (Chapter 9).

The tailpipe exhaust carries various other molecules, mainly CO, NO, NO₂, and unburned hydrocarbons. These are toxic pollutants, and their unused chemical energy also represents an energy inefficiency. The carbon monoxide and unburned hydrocarbons are the result of incomplete combustion (partial combustion) of the fuel. The two oxides of nitrogen—collectively called NOₓ—form from atmospheric oxygen and nitrogen, which combine under the influence of the engine's high temperatures. Cars and trucks produce about two-thirds of the nation's CO pollution, one-third of its hydrocarbon pollution, and half of its NOₓ pollution.

The automobile's main loss of useful energy occurs in the engine, mainly as a consequence of the second law. The engine's best possible, or ideal, efficiency is 30%, and its actual efficiency is 17 kW/69 kW = 25%. Several losses combine to

<p>| TABLE 7.2 |</p>
<table>
<thead>
<tr>
<th>Fuel for automobiles and trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel</strong></td>
</tr>
<tr>
<td>For internal combustion</td>
</tr>
<tr>
<td>Gasoline</td>
</tr>
<tr>
<td>Diesel fuel</td>
</tr>
<tr>
<td>Compressed natural gas</td>
</tr>
<tr>
<td>Liquefied natural gas</td>
</tr>
<tr>
<td>Liquefied petroleum gas (propane)</td>
</tr>
<tr>
<td>Methanol (wood alcohol)</td>
</tr>
<tr>
<td>Ethanol (corn alcohol)</td>
</tr>
<tr>
<td>Hydrogen*</td>
</tr>
<tr>
<td>For noncombustion</td>
</tr>
<tr>
<td>Storage batteries*</td>
</tr>
<tr>
<td>Hydrogen fuel cell*</td>
</tr>
</tbody>
</table>

*Since electricity for hydrogen production or for storage batteries can come from any source, the ultimate energy resource can be wind, hydroelectric, nuclear, coal, photovoltaics, and the like.
bring the engine’s efficiency from the maximum 30% allowable by the second law down to 25%; incomplete combustion, the formation of NOx, friction in the engine, and thermal losses through the engine’s wall.

Of the 17 kW of work produced by the engine, 5 kW go to internal devices like the water pump and air conditioner. The remaining 12 kW go to the transmission and drive train that couples the engine to the drive wheels. This coupling is about 75% efficient, so 9 kW finally arrive at the drive wheels.

The 9 kW carry the car down the road. About half of it goes into overcoming air resistance. Air resistance increases with speed and dominates at higher speeds. The other half goes into rolling resistance (Section 4.6), which dominates at lower speeds. The overall energy efficiency of the entire automobile (not just the engine) is 9/70 = 13%, or about one-eighth.

### 7.6 Transportation Efficiency

Our definition of energy efficiency—useful energy output divided by total energy input—doesn’t really capture the automobile’s purpose. Although its purpose is to move people, its energy goes mostly into moving the car itself rather than people. Gasoline mileage, the common measure of automobile efficiency, suffers from the same defect. Neither of these measures really captures people-moving efficiency, in other words, transportation efficiency. On the other hand, gasoline mileage is useful for comparing different cars with one another (Table 7.3, Figure 7.18).

The efficiency of using energy to move people can be directly measured by using as the output the number of passenger-kilometers delivered. For example, if a bus moves 20 passengers a distance of 3 km, it has delivered 20 passengers × 3 km = 60 passenger-km. Similarly, the efficiency of using energy to move goods can be directly measured by using as the useful output the number of tonne-kilometers delivered. For example, if a truck moves 5 tonnes a distance of 80 km, it has delivered 5 tonnes × 80 km = 400 tonne-km.
Table 7.3 lists the fuel efficiencies of four-passenger automobiles. Table 7.4 compares the passenger-moving and freight-moving efficiencies of several transportation modes. Walking and bicycling come out far ahead because no energy is put into moving a heavy vehicle and because no heat engine is employed; thus there is no loss due to the second law of thermodynamics. Bicycling is more efficient than walking because wheels keep rolling—wheels take advantage of the law of inertia. With each step, walking requires you to start and stop your legs—an acceleration, requiring a force, requiring you to do work. Trains are far more efficient than other vehicles because it is possible to overcome both the resistive forces acting on rolling vehicles (compare Figure 7.17). Because a train presents a small frontal area relative to its large load, its air resistance per kilogram of load is far below that of cars and trucks. And because a train rolls on steel wheels on steel tracks, there is little of the tire-squeezing that causes rolling resistance (see Section 4.6).
For fun, let’s look at transportation efficiencies throughout the animal kingdom. Which animal or machine is most efficient at moving itself and any passengers that might be along? Fruit flies? Horses? Jet planes? To compare fruit flies and horses fairly, we must incorporate the fact that the horse’s energy goes into moving a much larger mass. So the useful output should be measured as total body (or vehicle) mass times distance moved. Table 7.5 gives several such mass-moving efficiencies, in gram-kilometers per joule of energy. For vehicles such as the bicycle and the automobile, the total mass of the occupant(s) plus the vehicle is included as the output. Again, bicycling comes out far ahead, because animals don’t have wheels, and among the vehicles used for transportation, the bicycle is the only one that is not a heat engine.

Animals with wheels would have a big energy advantage. They have not evolved on Earth’s rough surface, but tumbleweeds take advantage of rolling in order to spread their seeds. One could speculate that on another planet with surfaces created by smooth lava flows, wheeled animals might evolve and be abundant!

**TABLE 7.5**

<table>
<thead>
<tr>
<th>Mass-moving efficiencies of animals and machines, in gram-kilometers per joule</th>
<th>g-km/J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human on bicycle</td>
<td>1.5</td>
</tr>
<tr>
<td>Salmon</td>
<td>0.6</td>
</tr>
<tr>
<td>Horse</td>
<td>0.5</td>
</tr>
<tr>
<td>Jet transport</td>
<td>0.4</td>
</tr>
<tr>
<td>Human walking</td>
<td>0.3</td>
</tr>
<tr>
<td>Automobile</td>
<td>0.3</td>
</tr>
<tr>
<td>Typical bird</td>
<td>0.2</td>
</tr>
<tr>
<td>Hummingbird</td>
<td>0.05</td>
</tr>
<tr>
<td>Fly, bee</td>
<td>0.02</td>
</tr>
<tr>
<td>Jet fighter</td>
<td>0.01</td>
</tr>
<tr>
<td>Mouse</td>
<td>0.005</td>
</tr>
</tbody>
</table>


**DIAGNOSE 5** You wish to move 130 tons of freight a distance of 100 miles. About how many gallons of gasoline (or gasoline equivalent) will you need to move it by truck? By air? By rail?

**DIAGNOSE 6 MAKING ESTIMATES** About how much gasoline would a 55-mph speed limit save every year, for an average American car and for all American cars? Use the following data: There are some 150 million cars in the United States; a typical car travels 15,000 miles in a year, about half of this being highway driving; American cars average 20 miles per gallon; and fuel mileage is about 15% worse at 65 mph (the approximate average speed without a 55 mph limit) than it is at 55 mph.

### 7.7 THE STEAM-ELECTRIC POWER PLANT

We turn now from the automobile to society’s other major heat engine, the steam-electric power plant.

Figure 7.19 is a schematic diagram of the operation of a typical coal-burning electric power plant. Coal is the most widely used primary energy source for electricity. Other plants that use oil, natural gas, nuclear energy, or solar energy to turn water into steam in a boiler operate much as a coal-burning plant does in producing energy from steam.

The coal combusts externally in a furnace, and its thermal energy is transferred to water inside a boiler. Most combustion products escape through the

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5. 130 tons × 100 miles = 13,000 ton-mi. Trucks use 1 gallon of gasoline for each 65 ton-mi (Table 7.4), so 13,000 ton-mi requires (13,000 ton-mi)/(65 ton-mi per gal) = 200 gallons. For the other two questions, it’s easiest to use proportions: Table 7.4 shows that air transport is one-fifth as efficient as truck transport, and so it requires five times more gasoline, or 1000 gallons. Rail transport is four times more efficient than truck transport, and so it requires one-fourth as much gasoline, or 50 gallons.

6. An individual car drives 7500 highway miles in 1 year. Compare driving this at 55 mph (getting about 20 miles per gallon) with driving it at 65 miles per hour (where fuel efficiency is 15% worse, or only 17 miles per gallon): 7500/20 = 375 gallons, 7500/17 = 441 gallons, so an extra 441 – 375 = 66 gallons is needed at the higher speed. For the entire U.S. auto fleet, 150 × 10⁸ × 66 gallons = 10 × 10⁹ gallons. This figure represents some 12% of U.S. oil imports.
stack but some pollutants are removed first. The boiler produces high-pressure steam at over 500°C, far above the normal boiling temperature. The steam moves through pipes to a large rotating device called a steam turbine that is designed to turn when it feels a higher pressure on the front (upstream) side than on the back (downstream) side. Like the piston in a car, the steam turbine is the key device that transforms thermal energy into work. The turbine turns an electric generator, a device containing wires and magnets that creates electricity when the turbine causes it to rotate.

**FIGURE 7.19**
A schematic diagram showing the operation of a coal-fueled steam-electric generating plant.
The rotating turbine extracts some of the hot steam's thermal energy and converts it to work. The second law tells us that this is possible only if the remaining thermal energy flows to a cooler temperature. To maintain the required temperature difference, the exhaust side of the turbine is cooled by an external stream or lake, or by evaporative cooling in the atmosphere.

To obtain the greatest efficiency, the exhaust is cooled sufficiently to turn the steam back into liquid water, because this greatly reduces the pressure against the back side of the turbine. The steam is then sucked forcefully through the turbine, from very high pressure on one side to a near vacuum on the other. Because the transition from steam to water is called condensation, the cooling device is called a condenser. Once condensed, pumps move the water back around to the boiler, where the cycle begins again.

As you can see by inspecting Figure 7.19, the plant is a heat engine. It converts thermal energy to work. Thermal energy flows in at the boiler and out at the condenser, and work is done by the turbine (compare Figure 7.5).

Figure 7.20 shows the energy flow. A large plant generates about 1000 MW of electric power, enough for a large city. Because a typical plant has an efficiency of about 40% (Table 7.1), this electrical output requires about 2500 MW, or 2500 million joules in every second, of energy input from coal or another fuel. Calorimetry experiments show that the combustion of 1 kilogram of coal produces about 25 million joules of thermal energy, so the plant requires 100 kilograms of coal every second.

Of the 2500 MW input, 300 MW go out through the stack, accompanied by gases, such as sulfur oxides (which cause acid rain) and CO₂ (which causes global warming), and small incombustible solid particles called ash. Modern plants remove about 90% of the sulfur oxides and 99% of the ash, which then presents a significant solid-waste disposal problem. The turbine converts the thermal en-

*In practice, not all of the steam is condensed; some of it is removed from the turbine's exhaust and reused without condensation to heat the water on its way to the boiler. Steam also is reused by being reheated and passed through lower-pressure turbines several times before finally going to the condenser.
ergy of steam to useful work at a rate of 1000 MW of power, which is in turn used to drive a generator that creates 1000 megawatts of electric power. The plant’s biggest loss in useful energy, the 1200 MW exhausted, is primarily an unavoidable consequence of the second law. This exhaust goes into the condenser’s cooling water. If the cooling water comes from a lake or river, the exhaust warms the water, an effect called thermal pollution. Many plants use the atmosphere as the coolant by employing large evaporative coolers known as cooling towers (Figure 7.21). Finally, some 100 MW of the generated electricity is transformed into thermal energy during transmission over electric power lines that might extend hundreds of miles, and 900 MW gets to the user.

- **DIALOGUE 7** How efficient is the boiler? The electric generator?

- **DIALOGUE 8 MAKING ESTIMATES** (a) Estimate the amount of coal (in tonnes) that this plant uses in one day. How many large highway truckloads of coal is this, at about 50 tonnes per truck? (b) Estimate the amount of carbon dioxide that this plant puts into the atmosphere every day. Hint: The oxygen atom’s mass is 33% larger than the carbon atom’s mass; for your estimate, treat their masses as roughly equal, and assume that coal is 100% carbon.

### 7.8 RESOURCE USE AND EXPONENTIAL GROWTH

Consideration of the social implications of energy raises many growth-related issues. As our growing numbers and environmental impact begin to affect the entire natural world, it is important that we analyze where all of this growth might be taking us.*

We begin with a familiar example. Suppose you invest $100 at a rate of return or growth rate of 10% per year. When will you double your money? You earn $10 during the first year, so you have $110. In the second year you earn $11, one dollar more than you earned the first year. Now you have $121, so you earn $12.10 during the next year. Each year you earn more than you did the previous year, because your percentage increase is the same each year.

Figure 7.22 graphs your account and compares it with a second graph that also increases by $10 during the first year but then follows a straight line. The second graph illustrates linear (straight line) growth, which increases by a fixed amount each year. As you can see, there is a big difference between $10 per year and 10% per year. When a quantity grows by a fixed percentage in each unit of time, its growth is said to be exponential.†

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7. 2200/2500 = 88%. For the generator, 1000 MW of input power (from the turbine) produces 1000 MW of electric power (a little less, really), so the generator is essentially 100% efficient.

8. (a) The number of seconds in a day is 60 s/min × 60 min/hr × 24 hr/day = 10^5 s. One hundred kilograms enter the plant every second, so the amount entering in a day is about 10^5 × 100 = 10^7 kg, or 10,000 tonnes. This is 10,000/50 = 200 large truckloads every day! (b) The CO₂ molecule is about three times as massive as the C atom. The mass of CO₂ created is thus three times the mass of coal consumed: 30,000 tonnes!

*This section draws on the work of University of Colorado physicist Albert A. Bartlett.

†It is called exponential because the account is worth 100 × 1.1 after 1 year, 100 × 1.1^2 after 2 years, 100 × 1.1^3 after 3 years, and so forth. The number of years is in the exponent.
Section 7.8 Resource Use and Exponential Growth

The arithmetic of growth is the forgotten fundamental of the energy crisis.

Albert Bartlett

Pressures resulting from unrestrained population growth put demands on the natural world that can overwhelm any efforts to achieve a sustainable future. If we are to halt the destruction of our environment, we must accept limits to that growth. . . . The United Nations concludes that the eventual total [world population] could reach 14 billion. . . . But, even at this moment, one person in five lives in absolute poverty without enough to eat, and one in ten suffers serious malnutrition. . . . We must stabilize population.


If you continue adding on 10% each year, your investment account will reach about $195 after 7 years. In 7 years, you will roughly double your money.

What will happen if you keep your money deposited for another 7 years? Since the same arithmetic applies, it will double again, to nearly $400. In the next 7 years it will double again, to nearly $800. And so forth. Exponential growth has a fixed, unchanging, doubling time.

Making Estimates

The exponential salary

Suppose you take a job requiring you to work every day for 30 days and your employer offers you just 1¢ for the first day and then a doubled salary every day for the 30 days. About how much will you earn on day 30?

SOLUTION Starting with 1¢ on day 1, you will earn $5.12 on day 10 (1, 2, 4, 8, 16, 32, 64, 128, 256, 512¢). Poverty wages! To simplify matters, round off the $5.12 to just $5. Now continue doubling. On day 20, your earnings will be $5120. Now you are getting rich. Round this off to $5000, and continue. On day 30 alone, your earnings are more than $5 million!

Exponential growth can be surprising, because our intuitions tend to be linear.

In a population of animals, the number of newborns each year is roughly proportional to the number of potential parents in the population that year. This

*If you aren’t convinced of this, think of it in this way: You begin the second 7-year period with about $200. Think of this as two $100 accounts. During the second 7-year period, each of these accounts must grow to about $200, so your total is $400.
The world is projected to add at least 960 million people during this decade, up from 840 million in the eighties and 750 million in the seventies.

WORLD POPULATION DATA SHEET, 1990

means that the percentage increase—the number of newborns divided by the total population—should be roughly the same from year to year. At least, this should be true so long as there are no offsetting deaths due to starvation or other consequences of large population size. This unchanging percentage increase means that the growth is exponential.

**Dialogue 9 Population Growth in a Finite Environment** Bacteria reproduce themselves by means of division. If you start with 1 bacterium, it will divide into 2; they will divide into 4, then into 8, and so forth. Since each population doubling occurs in the same time interval, it is an exponential process. Suppose that some strain of bacteria has a dividing time of 1 minute. You put 1 bacterium into a bottle at 11 A.M., and at noon you note that the bottle is full of bacteria. When was the bottle half full? If you were one of the bacteria, when might you have noticed that you were running out of space?

When you consume a finite resource exponentially, it is easy to use nearly all of it before you realize there is a problem (Figure 7.23). Continuing with Dialogue 9, suppose that at 11:55 A.M. some visionary bacteria, realizing they have a problem, launch an all-out search for new bottles. By 11:58 A.M., this program has been successful in discovering a huge, new reserve: three new bottles! It took the bacteria an entire hour to fill the first bottle. When will the new bottles be full? The answer is at 2 minutes past noon. Continued exponential growth eventually overwhelms all attempts to expand the resource base.

There is a simple and useful quantitative relation for exponential growth. Any increase in the growth rate must decrease the doubling time, so we might expect to find a relation between these two. It turns out that they are inversely proportional. The relation is, approximately,

\[
doubling \text{ time} \approx \frac{70}{\text{growth rate}}
\]

\[
T \approx \frac{70}{P}
\]

where \( T \) stands for the doubling time and \( P \) is the growth rate (the percentage growth per unit time, expressed in percent). This relation can also be turned around to read

\[
P \approx \frac{70}{T}
\]

Either quantity, the doubling time or the growth rate, is equal to 70 divided by the other quantity. For instance, the 10% savings account has a doubling time of \( T = \frac{70}{P} = \frac{70}{10} = 7 \) years.

9. Work backward from noon: The bottle must have been half full at 1 minute before noon. There is no single answer to the second question, but Figure 7.23, obtained by working backward from noon, gives a rough idea. A few forward-looking bacteria might begin to be concerned when the bottle got to be a few percent full, at a few minutes before noon.
For a significant historical example involving energy, we consider the growth of electric power in the United States. As you can see from examination of Figure 7.24, electric power production grew exponentially between 1935 and 1975, as it roughly doubled every 10 years during this period. The percentage growth rate between 1935 and 1975 was then $P = \frac{70}{T} = \frac{70}{10} = 7\%$ per year. What would the consequences have been if this growth rate had continued for very many years past 1975? In 1975, all of the electric energy in the United States could have been provided by about 400 large plants. If the 10-year doubling time had continued, 800 plants would have been needed in 1985, 1600 in 1995, 3200 in 2005, and 6400 in 2015. Sixty-four hundred power plants would mean an average of more than one hundred twenty-five in every state, with everybody living within a few miles of a large power plant!

Obviously, expansion at a fixed growth rate cannot be sustained forever. In fact, electric power production increased by 50% during the 15-year period between 1973 and 1988, for an average growth rate of $\frac{50}{15} \approx 3\%$ per year. Although growth continued, the growth rate declined from 7% to 3%. The dramatic shift in growth rate was caused by the Mideast oil embargo, which raised energy prices, which depressed energy consumption.

U.S. oil production illustrates what can eventually happen when a finite resource is consumed exponentially. Like many industries, oil production grew exponentially during its early years, maintaining a growth rate of 8% per year between 1870 and 1930. But this could not be maintained, because the United States' recoverable oil resources (the oil that is economically feasible to recover) would be gone by now. The growth rate declined, and then around 1970 U.S. oil production in the forty-eight contiguous states began to drop.

Figure 7.25 shows the bell-shaped graph that is typical for the yearly production of a nonrenewable resource—a resource that cannot be readily replaced.