CHAPTER 6

The Dynamics of Heat

6.1 HEAT AS A FORM OF ENERGY

Consider a book sent sliding across a tabletop. If the surface is rough, it will exert a fairly large frictional force on the book, and the book will soon come to a stop as its kinetic energy rapidly disappears. No corresponding increase in potential energy will occur, since there is no change in height. It appears that, in this example, mechanical energy is not conserved.

However, close examination of the book and the tabletop would show that they are slightly warmer than before. The disappearance of kinetic energy of the book is accompanied by the appearance of *heat*. This suggests, though by no means proves, that the kinetic energy of the book was transformed into heat. If so, heat must be one form of energy. This section deals with how the idea of heat as a form of energy gained acceptance. You will see how theory was aided by practical knowledge of the relationship between heat and work.

Until about the middle of the nineteenth century, heat was generally thought to be some kind of fluid, called *caloric fluid*. No heat is lost or gained overall when hot and cold bodies are mixed; for example, mixing equal amounts of boiling water (100°C) and nearly freezing water (0°C) produces water at just about 50°C. One could therefore conclude that the caloric fluid is conserved in that kind of experiment. Some substances, like wood or coal, seemed to have locked up the caloric fluid, which is then released during combustion.

Although the idea that the heat content of a substance is represented by a quantity of conserved fluid was an apparently useful one, it does not adequately explain some phenomena involving heat. Friction, for example, was known to produce heat (e.g., just rub your hands together rapidly). But it was difficult to understand how the conservation of caloric fluid applied to friction.

In the late eighteenth century, while boring cannon for the Elector of Bavaria, Benjamin Thompson (Count Rumford) observed that a great deal of heat was generated. Some of the cannon shavings—provided by the work done on the metal by a drill—were hot enough to glow. Rumford made some careful measurements by immersing the cannon in water and measuring the rate at which the temperature rose. His results showed that so much heat evolved that the cannon would have melted had it not been cooled. From many such experiments, Rumford concluded that heat is not

FIGURE 6.1 Benjamin Thompson was born in Woburn, Massachusetts, in 1753. After several years as a shopkeeper's apprentice, he married a rich widow and moved to Concord (then called Rumford). During the Revolution, Thompson was a Tory; he left with the British army for England when Boston was taken by the rebels. In 1783, Thompson left England and ultimately settled in Bavaria, where he designed fortifications and built munitions and served as an administrator. The King of Bavaria was sufficiently impressed to make him a Count in 1790, and Thompson took the name Rumford. In 1799, he returned to England and continued to work on scientific experiments. Rumford was one of the founders of the Royal Institution. In 1804 he married Lavoisier's widow; the marriage was an unhappy one, and they soon separated. Rumford died in France in 1814, leaving his estate to institutions in the United States.

a conserved fluid but is generated when work is done, and it continues to appear without limit as long as work is done. His estimate of the ratio of heat produced to work performed was within an order of magnitude ("power of ten") of the presently accepted value.

Rumford's experiments and similar work by Humphry Davy at the Royal Institution in London did not convince many scientists at the time. The reason may have been that Rumford could give no clear suggestion of just what heat is, at least not in terms that were compatible with the accepted models for matter at that time.

Nearly a half-century later, James Prescott Joule repeated on a smaller scale some of Rumford's experiments. Starting in the 1840s and continuing for many years, Joule refined and elaborated his apparatus and his techniques. In all cases, the more careful he was, the more exact was the proportionality of the quantity of heat, as measured by a change in temperature, and the amount of work done. Here, Joule, like others, made the assumption that the quantity of heat produced, say, in water, symbolized by ΔQ (Q is the usual symbol for heat), is equal to the mass of the water times the change of its temperature, ΔT:

$$\Delta Q = m\,\Delta T.$$

Today, we know that the amount of heat corresponding to a given temperature change is different for different substances being heated. In order to take this into account, the constant c, called the *specific heat*, is introduced into the above equation. In the metric system of units, the specific heat c is the amount of heat, measured in the units of calories, required to raise 1 g of the substance by 1°C under standard conditions (i.e., at prescribed temperature and pressure) and without any loss of heat to the surroundings. So the relationship between heat and temperature may be written

$$\Delta Q = m\,c\,\Delta T.$$

In order to define a *calorie* of heat, the specific heat of water under standard conditions is defined as c = 1 cal/g°C. In other words, 1 cal is defined as the amount of heat required to raise the temperature of 1 g of water by 1°C under standard conditions. So, in these units, and with water as the material being heated, we have

$$\Delta Q = m\,\Delta T.$$

For one of his early experiments on the relationship between heat and work, Joule constructed a simple electric generator, which was driven by a falling weight. The electric current that was generated heated a wire. The

FIGURE 6.2 James Prescott Joule (1818–1889). Joule was the son of a wealthy Manchester brewer. His arduous experiments were initially motivated by the desire to develop more efficient engines for the family brewery.

wire was immersed in a container of water, which it heated. From the distance that the weight descended Joule calculated the work done (the decrease in gravitational potential energy). The product of the mass of the water and its temperature rise allowed him to calculate the amount of heat produced. In another experiment, Joule compressed gas in a bottle immersed in water, measuring the amount of work done to compress the gas. He then measured the amount of heat given to the water as the gas grew hotter on compression.

Joule's most famous experiments involved an apparatus in which slowly descending weights turned a paddle wheel in a container of water. Owing to the friction between the wheel and the liquid, the wheel performed work on the liquid, raising its temperature.

All these experiments, some repeated many times with improved apparatus, led Joule to announce two very important, quantitative results in 1849. As expressed in modern terms and units, they are as follows:

- The quantity of heat produced by the friction of bodies, whether solid or liquid, is always proportional to the quantity of energy expended.
- The quantity of heat (in calories) capable of increasing the temperature of 1 kg of water by 1°C requires for its evolution the change of me-

> chanical energy represented by the fall of a weight of 4180 N through the distance of 1 m.

Joule's first statement in the above quote is the evidence that heat is a form of energy, contrary to the caloric theory that heat is a fluid. The second statement gives the numerical magnitude of the ratio he had found of mechanical energy to the equivalent heat energy. The ratio of the mechanical energy, E, to the equivalent amount of heat energy, Q, is generally called the *mechanical equivalent of heat*. Its value, by the most recent measurements, is 4.18×10^3 joules/Calorie in the mks system of units, where Calorie (with a capital C) is 1000 calories (often abbreviated "kcal"). In the cgs system of units, the mechanical equivalent of heat is 4.18×10^5 erg/calorie. (See the insert for review.)

By the time Joule performed his famous experiments, the idea that heat is a form of energy was slowly gaining acceptance. Joule's experiments served as a strong argument in favor of that idea.

UNITS

A reminder: In the metric system used today in most countries, quantities are measured using either grams, centimeters, and seconds (cgs units) or kilograms, meters, and seconds (mks units). (See the discussion in the *Student Guide*.) You saw in Chapter 5 that mechanical energy in mks units is expressed as joules (J) and in cgs units as ergs:

$$1 \text{ J} = 1 \text{ kg m}^2/\text{s}^2 = 1 \text{ N} \cdot \text{m (newton-meter)},$$

$$1 \text{ erg} = 1 \text{ g cm}^2/\text{s}^2 = 1 \text{ D} \cdot \text{cm (dyne-centimeter)}.$$

As indicated on page 255, heat energy in cgs units is expressed as calories (abbreviated as cal), while in mks units heat energy is expressed in kilocalories (1000 calories), which is often written either as kcal or with an uppercase initial C, Calorie. (The Calorie, abbreviated as Cal, is also the measure used to express the energy content in food.) These units are summarized in the table below, along with the modern values for the mechanical equivalent of heat.

Units	*Mechanical energy*	*Heat energy*	*$J = W/Q$*
mks	joule (J)	Calorie, kcal	4.18×10^3 J/Cal
cgs	erg	calorie	4.18×10^7 erg/cal
English	foot-pound (ft-lb)	Btu	1.29×10^{-3} ft-lb/Btu

6.2 THE STEAM ENGINE AND THE INDUSTRIAL REVOLUTION

The development of the modern science of heat was closely tied to the development of the modern technology of engines designed to perform useful work. For millennia until about two centuries ago, most work was done by people or by animals. Wind and water also provided mechanical work, but these were generally unreliable as sources of energy. For one thing, they were not always available when and where they were needed.

In the eighteenth century, miners began to dig deeper and deeper in search of a greater coal supply. Water tended to seep in and flood these deeper mines. The need arose for an economical method of pumping water out of these mines. The steam engine was developed initially to meet this very practical need.

The steam engine is a device for converting the heat energy of heat-producing fuel into mechanical work. For example, the chemical energy of wood, coal, or oil, or the nuclear energy of uranium, can be converted into heat. The heat energy in turn is used to boil water to form steam, and the energy in the steam is then turned into mechanical energy. This mechanical energy can be used directly to perform work, as in a steam locomotive, used to pump water, or to transport loads, or is transformed into electrical energy. In typical industrial societies today, most of the energy used in fac-

FIGURE 6.3 Camel driving a water wheel.

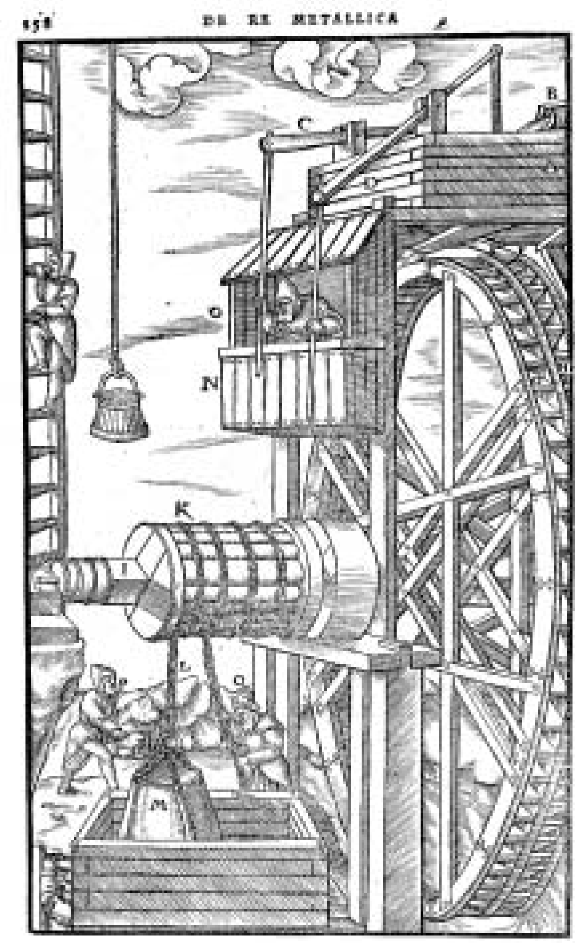


FIGURE 6.4 Woodcut from Georgius Agricola's *De Re Metallica* (1556), a book on mining techniques in the sixteenth century.

tories and in homes comes from electrical energy. Falling water is used to generate electricity in some areas, but steam-powered generators still generate most of the electrical energy used in the United States today. (This is further discussed in Chapter 11.) There are other devices that convert fuel to heat energy for the production of mechanical energy, such as internal combustion engines used in cars and trucks, for example. But the steam engine remains a good model for the basic operation of the whole family of so-called *heat engines*, and the chain of processes from heat input to work output and heat exhaust is a good model of the basic *cycle* involved in all heat engines.

Since ancient times, people knew that heat can be used to produce steam, which can then do mechanical work. One example was the "aeolipile," in-

FIGURE 6.5 Old windmill and new wind turbine.

vented by Heron of Alexandria about A.D. 100. (See Figure 6.6.) It worked on the principle of the rotating lawn sprinkler, except that the driving force was steam instead of water pressure. Heron's aeolipile was a toy, meant to entertain rather than to do any useful work. Perhaps the most "useful" application of steam in the ancient world was another of Heron's inventions. This steam-driven device astonished worshipers in a temple by causing a door to open when a fire was built on the altar.

Not until late in the eighteenth century, however, did inventors develop commercially successful steam engines. Thomas Savery (1650–1715), an English military engineer, invented the first such engine. It could pump water out of a mine by alternately filling a tank with high-pressure steam, driving the water up and out of the tank, and then condensing the steam, drawing more water into the tank.

Unfortunately, inherent in the Savery engine's use of high-pressure steam was a serious risk of boiler or cylinder explosions. Thomas Newcomen (1663–1729), another English engineer, remedied this defect. Newcomen invented an engine that used steam at lower pressure (see Figure 6.7). His engine was superior in other ways also. For example, it could raise loads other than water. Instead of using the steam to force water into and out of

FIGURE 6.6 A model of Heron's aeolipile. Steam produced in the boiler escapes through the nozzles on the sphere, causing the sphere to rotate.

a cylinder, Newcomen used the steam to force a piston forward and air pressure to force it back. The motion of the piston could then be used to drive a pump or other engine. It is the back-and-forth force provided by the motion of the piston in a steam engine that is one origin of the definition of mechanical work, W, as force × distance, $W = Fd$.

The Newcomen engine was widely used in Britain and other European countries throughout the eighteenth century. By modern standards, it was not a very good engine. It burned a large amount of coal but did only a

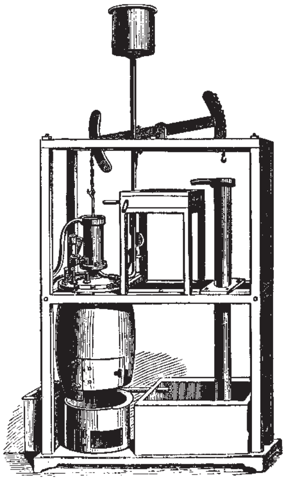


FIGURE 6.7 Model of the Newcomen engine, which inspired Watt to conceive of the separation of condenser and piston.

small amount of work at a slow, jerky rate. But the great demand for machines to pump water from mines produced a good market, even for that uneconomical engine.

The work of a Scotsman, James Watt, led to a greatly improved steam engine and one that had profound economic consequences. Watt's father was a carpenter with a successful business selling equipment to shipowners. James Watt was in poor health much of his life and gained most of his early education at home. In his father's attic workshop, he developed considerable skill in using tools. He wanted to become an instrument maker and went to London to learn the trade. Upon his return to Scotland in 1757, he obtained a position as instrument maker at the University of Glasgow.

In the winter of 1763–1764, Watt was asked to repair a model of Newcomen's engine that was used for demonstration lectures at the university. In acquainting himself with the model, Watt was impressed by how much steam was required to run the engine. He undertook a series of experiments on the behavior of steam and found that a major problem was the temperature of the cylinder walls. Newcomen's engine wasted most of its heat in warming the walls of its cylinder, since the walls were cooled on each cycle as cold water was injected to condense the steam, forcing the piston back under air pressure.

Early in 1765, Watt remedied this wasteful defect by devising a modified type of steam engine. (See Figure 6.8.) In retrospect, it sounds like a simple idea. After pushing the piston up, the steam was admitted to a *separate* container, called the *condenser*, where the steam condensed at a low temperature. With this system, the *cylinder* containing the piston could be kept hot all the time, and the condenser could be kept cool all the time.

The use of the separate condenser allowed huge fuel savings. Watt's engine could do twice as much work as Newcomen's with the same amount of fuel. Watt also added many other refinements, such as automatically controlled valves that were opened and closed by the reciprocating action of the piston itself, as well as a *governor* that controlled the amount of steam reaching the engine, to maintain a constant speed for the engine (see Figure 6.9). The latter idea of using part of the output of the process to regulate the process itself, is called *feedback*. It is an essential part of the design of many modern mechanical and electronic systems.

Like Thomas Edison later, or successful computer technologists in our day, Watt and his associates were good businessmen as well as good engineers. They made a fortune manufacturing and selling the improved steam engines. Watt's inventions stimulated the development of engines that could do many other jobs. Steam drove machines in factories, railway locomotives,

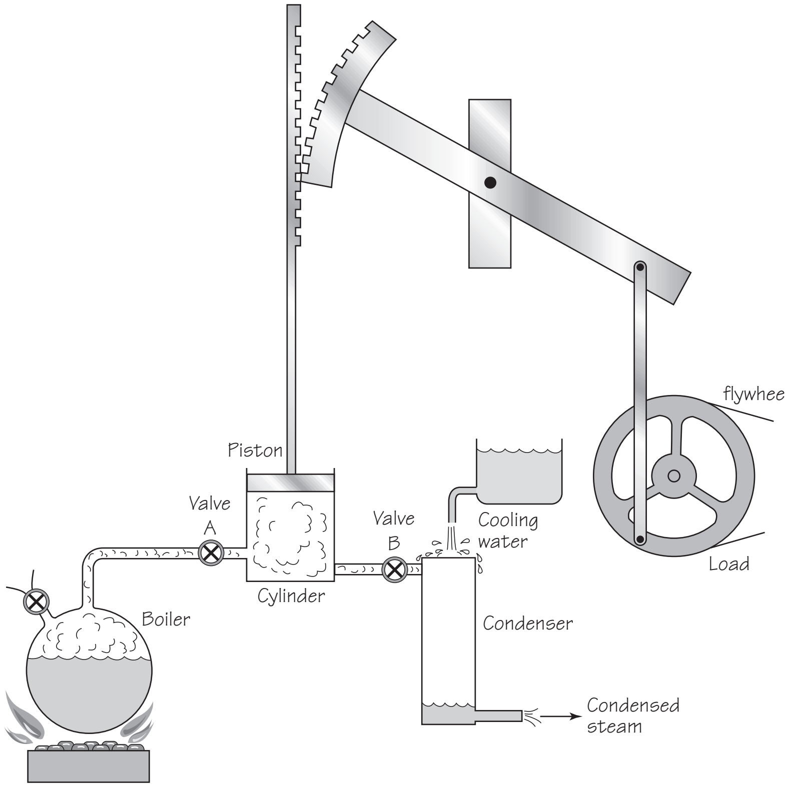


FIGURE 6.8 Schematic diagram of Watt's steam engine. With valve A open and valve B closed, steam under pressure enters the cylinder and pushes the piston upward. When the piston nears the top of the cylinder, valve A is closed to shut off the steam supply. Then valve B is opened, so that steam leaves the cylinder and enters the condenser. The condenser is kept cool by water flowing over it, so the steam condenses. As steam leaves the cylinder, the pressure there decreases. Atmospheric pressure (helped by the inertia of the flywheel) pushes the piston down. When the piston reaches the bottom of the cylinder, valve B is closed, and valve A is opened, starting the cycle again. Valves A and B are connected to the piston directly, so that the motion of the piston itself operates them.

steamboats, and even early steam cars. Watt's engine gave an enormous stimulus to the growth of industry in Europe and America. It thereby helped transform the economic and social structure of industrial civilization.

The widespread development of engines and machines revolutionized the mass production of consumer goods, construction, and transportation. The average standard of living in Western Europe and the United States

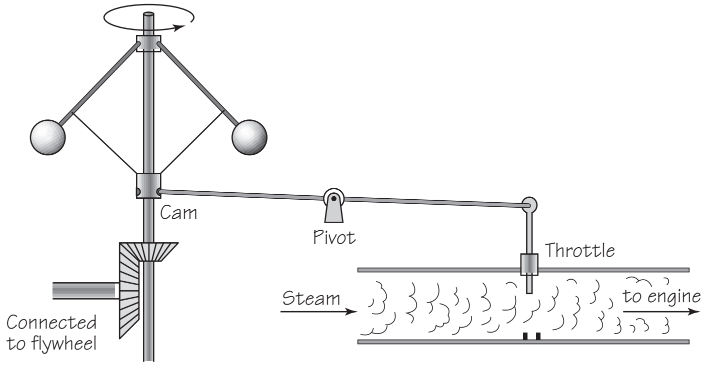


FIGURE 6.9 Watt's "governor." If the engine speeds up for some reason, the heavy balls swing out to rotate in larger circles. They are pivoted at the top, so the sleeve below is pulled up. The cam that fits against the sleeve is therefore also pulled up; this forces the throttle to move down and close a bit. The reduction in steam reaching the engine thus slows it down again. The opposite happens when the engine starts to slow down. The net result is that the engine tends to operate at nearly a stable level.

rose sharply. It is difficult for most people in the industrially "developed" countries to imagine what life was like before this "Industrial Revolution." But not all the effects of industrialization have been beneficial. The nineteenth-century factory system provided an opportunity for some greedy and cruel employers to treat workers almost like slaves. With no labor laws or even child protection laws, those employers made huge profits while keeping employees and their families on the edge of starvation.

FIGURE 6.10 Steam-powered locomotive.

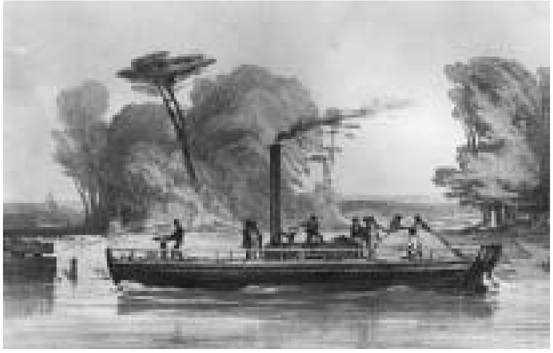


FIGURE 6.11 The *Charlotte Dundas*, the first practical steamboat, built by William Symington, an engineer who had patented his own improved steam engine. It was tried out on the Forth and Clyde Canal in 1801.

This situation, which was especially serious in England early in the nineteenth century, led to demands for reform. New laws eventually eliminated the worst excesses.

More and more people left the farms, either voluntarily or forced by poverty and new land laws, to work in factories. Conflict grew intense between the working class, made up of employees, and the middle class, made up of employers and professionals. At the same time, some artists and intellectuals, many of the Romantic movement, began to attack the new tendencies of their society. They saw this society becoming increasingly dom-

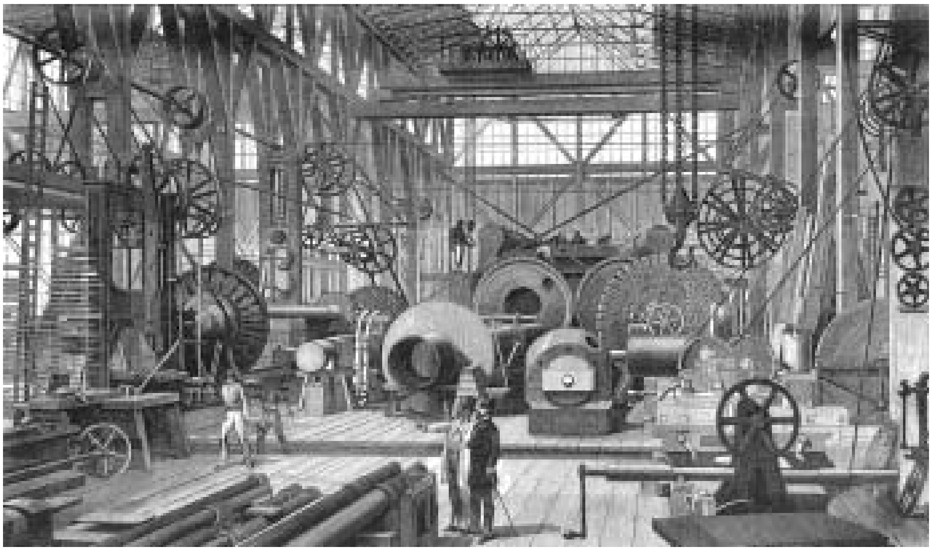


FIGURE 6.12 Engraving of an early steam-powered factory. Matthew Boulton (Watt's business partner) proclaimed to Boswell (biographer of Samuel Johnson): "I sell here, sir, what all the world desires to have: POWER!"

■ AGRICULTURAL STEAM TECHNOLOGY

There are three distinct operations in the harvesting of grain. Reaping, which is cutting the stem from the ground, threshing which is separating the grain from the kernel, and winnowing which cleans the grain from the chaff.

Hand-reaping methods, using first sickles and then scythes for millennia, were only replaced by new methods employing mechanical machinery in the first half of the nineteenth century. In the 1830s Hiriam Moore, a farmer in Michigan, began to design a machine known as a combine that would use horsepower to cut, thresh, and clean.

The next important breakthrough came from George Berry, a wheat farmer in the Sacramento Valley. Although he had been impressed by the reduction in labor costs resulting from the introduction of the combine, Berry had seen many of his horses die in the intense heat of July and August harvesting. Berry decided to use the steam-traction engines that had begun to appear on some farms to power his own combine. The combine was moved forward by a 26-horsepower steam-traction engine, while a smaller, stationary 6-horsepower steam-traction engine powered the cutter, thresher, and separator.

The steam-traction engines were used not only to power combines, but also for plowing, planting, and cultivation as well. However, a different engine was used for each different job, and few farmers could justify this kind of expenditure on machinery. In 1921, Alexander Legge, general manager of International Harvester Company, authorized his company to begin developing an all-purpose engine. The new tractor became known as the Farmall, and it was the first engine that truly achieved George Berry's vision of replacing horses in farming.

Further Reading

C. Canine, *Dream Reaper* (Chicago, University of Chicago Press, 1997).

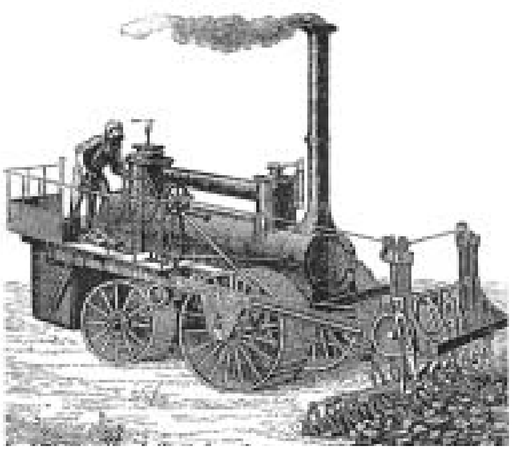


FIGURE 6.13 Nineteenth-century French steam cultivator

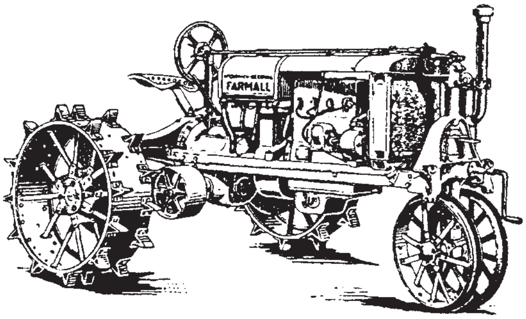


FIGURE 6.14 The Farmall: "It would be tall and maneuverable enough to cultivate row crops, yet it would still have the power to plow, pull implements, and deliver belt power to threshers, grinders, and crop elevators."

inated by commerce, machinery, and an emphasis on material goods. In some cases, they confused research science itself with its technical applications (as is still done today). Sometimes they accused scientists of explaining away all the awesome mysteries of nature. These artists denounced both science and technology, while often refusing to learn anything about them. A poem by William Blake contains the questions:

> And did the Countenance Divine
>   Shine forth upon our clouded hills?
> And was Jerusalem builded here
>   Among these dark Satanic mills?

Elsewhere, Blake advised his readers "To cast off Bacon, Locke, and Newton." John Keats was complaining about science when he included in a poem the line:

> Do not all charms fly
> At the mere touch of cold philosophy?

These attitudes are part of an old tradition, going back to the ancient Greek opponents of Democritus' atomism. As noted in Chapter 4, many of the Romantic writers and artists attacked Galilean and Newtonian physics for supposedly distorting moral values. The same type of accusation can still be heard today.

6.3 POWER AND EFFICIENCY OF ENGINES

The usefulness of an engine for many tasks is given by the rate at which it can deliver energy. The rate at which an engine delivers energy is called its *power*. By definition, the power (P) is the amount of energy (E) delivered per unit of time (t):

$$P = \frac{E}{t}.$$

As with energy, there are many common units of power with definitions rooted in tradition. Before the steam engine, the standard source of power was the workhorse. Watt, in order to rate his engines in a unit people could understand, measured the power output of a horse. He found that a strong horse, working steadily, could lift an object of 75-kg mass, which weighed about 750 N, at a speed of about 1 m/s (of course, Watt used the units of pounds and feet). The "horsepower" unit is still used today, but its value is now given by definition, not by experiment.

In metric units, the unit of power is appropriately named the watt, symbol W, which is not to be confused with the symbol W for "work." (You can usually tell from the context which unit is intended.) One watt is defined as one joule of energy per second, or in symbols, 1 W = 1 J/s. Thus, Watt's horse had a power rating of about 750 W. This means that in this case one horsepower was about 750 W. It is a curious case of the persistence of ancient habits that the unit "horsepower" is still used today, for example, for rating car engines and electric motors.

A further example: A light bulb rated at 100 W is using energy at the rate of 100 J/s. To find the total energy the bulb uses in a specific case, we need to specify the time interval during which it is on. Once the time is specified, and if the power usage is known, the energy can be found (from $P = E/t$) by multiplying the time and the power. In a typical case, the energy E used by a 100-W bulb during a period of, say, 10 hr is

$$\begin{aligned} E = P \cdot t &= (100\ \text{W})\ (10\ \text{hr}) \\ &= 1000\ \text{W} \cdot \text{hr} = 1\ \text{kWhr}, \\ 1\ \text{kWhr} &= (1000\ \text{J/s})(1\ \text{hr})(3600\ \text{s/hr}) \\ &= 3.6 \times 10^6\ \text{J}. \end{aligned}$$

The answer is over three million joules! Since the amount of energy consumed is so large, the commercial energy used by a typical home is billed in units of kilowatt-hours (kW-hr). Look at the monthly bill for your home's use of electricity and see how much electric energy is used, and what it costs effectively per kW-hr. (Then perhaps consider how to cut down on the home's use of electricity.)

Efficiency

Section 6.1 showed that the amount of mechanical energy corresponding to a unit of heat energy is known as the "mechanical equivalent of heat." Joule's finding a value for the mechanical equivalent of heat made it possible to describe engines in a new way. The concept of *efficiency* can be applied to an engine or to any device that transforms energy from one form to another, such as from heat energy into mechanical energy. *Efficiency is* *defined as the ratio of the useful output energy to the amount of input energy*. If E_{in} is input energy and E_{out} is the useful output, then efficiency (eff), can be defined in symbols

$$\text{eff} = \frac{\text{useful } E_{\text{out}}}{E_{\text{in}}}.$$

Efficiency may also be expressed as a percentage

$$\text{eff (\%)} = \left(\frac{\text{useful } E_{\text{out}}}{E_{\text{in}}}\right) \times 100.$$

Since energy cannot be lost, the greatest possible efficiency of any engine would be 100%, which would occur when *all* of the input energy appears as useful output. Obviously, efficiency must be considered as seriously as power output in designing engines. Fuel is, after all, a part of the cost of running an engine, and the more efficient an engine is, the cheaper it is to run.

Watt's engine was more efficient than Newcomen's, which in turn was more efficient than Savery's. Is there any limit to improvements in efficiency? The upper limit, 100%, is of course imposed by the law of energy conservation. That is, no engine can put out more mechanical energy than the energy put into it. But even before that law had been formulated, a young French engineer, Sadi Carnot, established that there is in practice a much lower limit. The reasons for this limit are just as fundamental as the law of energy conservation.

6.4 CARNOT AND THE BEGINNINGS OF THERMODYNAMICS

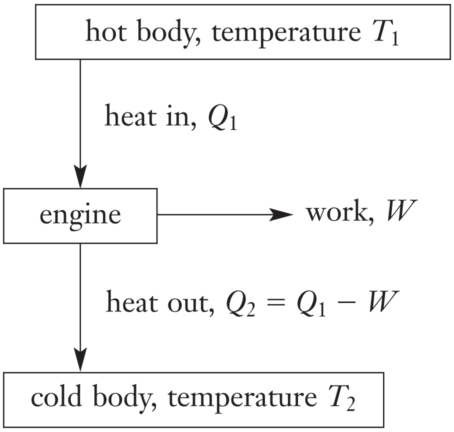
Carnot was one of a group of French engineers who had set out to study the scientific principles underlying the operation of the steam engine with the goal of achieving maximum power output at maximum efficiency. As a result of their studies, Carnot and others helped to establish the physics of heat, which is known as *thermodynamics*.

Carnot started with the experimentally obtained fact that heat does not by itself flow from a cold body to a hot one. It then follows that if, in a given situation, heat is made to flow from cold to hot, some other change

FIGURE 6.15 Sadi Carnot (1796–1832). Son of one of Napoleon's most trusted generals, Sadi Carnot was one of the new generation of expert administrators who hoped to produce a new enlightened order in Europe. He died of cholera in Paris at the age of 36.

must take place elsewhere. Some work must be done. Using an elegant argument, which is summarized in the materials for this chapter in the *Student Guide*, Carnot showed that no engine can be more efficient than an ideal, reversible engine, and that all such engines have the same efficiency. A *reversible engine is one in which the cycle from input energy to output work and exhausted energy, then back to input energy, can be run in reverse without any loss or gain of heat or other forms of energy*. For example, a refrigerator or an air conditioner is also a "heat engine," but its cycle operates in reverse fashion to a steam engine or automobile engine. It *takes in* work (in the form of electrical or mechanical power) to pump heat from a cold body (from inside the cold compartment or room) to a hotter one (the outside room or outside air). Naturally, because of friction and other outside effects, a truly reversible engine cannot be realized in practice, but it can be approached.

Since all reversible engines have the same efficiency, one has only to choose a simple version of a reversible engine and calculate its efficiency for one cycle to find an upper limit to the efficiency of any engine. Such a simple engine is depicted schematically in the diagram below. During one cycle of operation, the engine, represented by the small rectangle, takes in heat energy Q_1 from the hot body, produces useful work W, and exhausts some wasted heat energy Q_2 to the cold body. The cycle may then be repeated many times.



$$\text{efficiency} = \frac{\text{work out}}{\text{heat in}} = \frac{W}{Q_1}$$

$$= \left(1 - \frac{T_2}{T_1}\right)$$

Carnot calculated the efficiency of this schematic engine cycle and found that the ratios of heat and work in such a reversible engine depend only on the temperature of the hot substance from which the engine obtains its heat and on the temperature of the cold substance that extracts the waste heat from the engine. The temperatures used in this case are called *absolute*, or *Kelvin*, temperatures (named for Lord Kelvin who first introduced this scale). On the absolute scale, temperature measurements are equal to temperatures (t) on the Celsius scale (°C) plus 273. (Following current standard practice, no degree sign, °, is used for degrees Kelvin; the symbol used is K.)

$$T \text{ (absolute, in K)} = t \text{ (Celsius, in °C)} + 273.$$

Thus, on the Kelvin scale, water freezes at 273 K, while "absolute zero," $T = 0$ K, is

$$t = -273°\text{C}.$$

The expression found by Carnot for the efficiency of reversible engines, in modern terms, is

$$\text{efficiency} = \frac{\text{work out}}{\text{heat in}} = \frac{W}{Q_1} = \left(1 - \frac{T_2}{T_1}\right)$$

Although Carnot did not write the formula this way, we are making use of the fact that heat and energy are equivalent.

Notice that unless T_2, the temperature of the cold body that receives the exhaust from the engine, is 0 K—an unattainably low temperature—no engine can have an efficiency of 1 (or 100%). *This means that every engine must exhaust some "waste" heat to the outside before returning to get more energy from the hot body.*

In steam engines, the "hot body" is the steam fresh from the boiler, and the waste heat is extracted at the condenser. The *cycle* starts with the piston in the cylinder at rest. Steam is let into the cylinder at high temperature and pressure. The steam expands against the piston, performing work on the piston and ultimately on the outside surroundings. As the space occupied by the steam increases, the steam cools down. The steam cools further as it is let into the condenser, where it condenses into water. Air pressure then works on the piston, pushing it back into the cylinder, until it returns to where it started, thus completing one cycle.

As you see, the engine could not operate without a condenser to remove the heat from the steam after it had caused the piston to move forward, thus enabling the cylinder to be filled once again with steam. In an internal combustion engine (a car engine, for example), the "hot body" is the gasoline vapor inside the cylinder just as it explodes, and the cold substance is the exhaust. Any engine that derives its mechanical energy from heat must also be cooled to remove the "waste" heat at a lower temperature. If there is any friction or other inefficiency in the engine, it will add further heat to the waste and reduce the efficiency to below the theoretical limit of an ideal engine.

However, despite the inefficiencies of all real engines, it is important to know that none of the total energy is destroyed. Rather than being destroyed, the part of the energy that is extracted at the exhaust is unavailable for doing work. For instance, the exhausted heat cannot be recycled as input energy to run the engine to produce more useful work and thus increase the efficiency of the engine, by reducing the amount of waste energy because the input reservoir of heat is at a higher temperature than the output, and heat does not flow of its own accord from cold to hot.

The generalization of Carnot's finding is now known as one expression of the *second law of thermodynamics*. It is equivalent to Carnot's earlier observation that *heat does not by itself flow from a cold body to a hot one*. The need for air conditioners and refrigerators makes this abundantly clear.

The second law of thermodynamics, of which more will be said in Section 6.6, is recognized as one of the most powerful laws of physics. Even in simple situations it can help explain natural phenomena and the fundamental limits of technology.

Some Examples of Carnot's Result

If you burn oil to heat your home, the furnace requires some inefficiency to burn cleanly, so some heat is lost out the chimney. But recent advances in boiler technology have resulted in boilers with rated efficiencies as high as 0.86, or 86%.

If you install "flameless electric heat," which uses electric heating elements placed along the floor where it meets the wall, the electric power company still has to burn oil, coal, or natural gas in a boiler, use the steam to generate electricity, and deliver the electricity to your home. Because metals melt above a certain temperature and because the cooling water never gets below freezing, Carnot's finding makes it impossible to make the efficiency of electrical generation greater than about 60%. Since the power company's boiler also loses some of its energy out the chimney, and since the electricity loses some of its energy on the way from the power plant, only about one-quarter to one-third of the energy originally in the fuel actually makes it to your home. Obviously, electric heating wastes a lot of irreplaceable fossil fuel.

For steam engines the coldest temperature feasible for T_2 is about 280 K. (Why?) The hottest possible temperature for T_1 is about 780 K. So the maximum efficiency is 0.64.

Because of the limits placed by Carnot's finding on heat engines, it is sometimes important not only to give the actual efficiency of a heat engine but also to specify how close it comes to the maximum possible. The more carefully you look at a process, the more information is seen to be important. Home-heating apparatus and many large electrical heat-engine devices, such as refrigerators and air conditioners, now come with an "energy guide" sticker indicating the efficiency of the apparatus and the potential annual savings in electricity costs. Some states may even reward consumers with a rebate for making an energy-efficient purchase.

6.5 ARRIVING AT A GENERAL CONSERVATION LAW

The law of conservation of *mechanical* energy was presented in Section 5.11. This law applies only to "closed systems," i.e., to situations where no work is done on or by the system, and where no mechanical energy is transformed into heat energy or vice versa. Early in the nineteenth century, developments in science, engineering, and philosophy suggested new ideas about energy. It appeared that all forms of energy (including heat) could be transformed into one another with no loss. Therefore, it appeared that the total amount of energy in nature, that is, the Universe, must remain constant.

In 1800 Italian scientist Alessandro Volta invented the electric battery, demonstrating that chemical reactions could produce electricity. It was soon found that electric currents could produce heat and light, as in passing through a thin wire. In 1820, Hans Christian Oersted, a Danish physicist, discovered that an electric current produces magnetic effects. In 1831, Michael Faraday, the English scientist, discovered electromagnetic induction. When a magnet moves near a coil or a wire, an electric current is produced in the coil or wire. To some thinkers, these discoveries (discussed further in Chapter 11) suggested that all of the phenomena of nature were somehow united. Perhaps all natural events result from the same basic "force." This idea, though vague and imprecise, eventually bore fruit in the form of the *law of conservation of energy*, one of the most important laws in all of science:

> Natural events may involve a transformation of energy from one form to another; but the total quantity of energy does not change during the transformation.

Joule began his long series of experiments by investigating the "duty" of electric motors. In this case, duty was measured by the work the motor could do when a certain amount of zinc was used up in the battery that ran the motor. Joule's interest was to see whether motors could be made economically competitive with steam engines.

The invention and use of steam engines helped in establishing the law of conservation of energy (often abbreviated LCE) by showing how to measure energy changes. For example, Joule used the work done by descending weights driving a paddle wheel in a tank of water as a measure of the amount of gravitational potential energy transformed into heat energy in the water by its friction with the paddles.

In 1843, Joule stated that in such experiments, whenever a certain amount of mechanical energy seemed to disappear, a definite amount of heat always appeared. To him, this was an indication of the conservation of what we now call energy. Joule said that he was

> . . . satisfied that the grand agents of nature are by the Creator's fiat *indestructible;* and that, wherever mechanical [energy] is expended, an exact equivalent of heat is *always* obtained.

Joule was basically a practical man who had little time to speculate about a deeper philosophical meaning of his findings. But others, though using speculative arguments, were also concluding that the total amount of energy in the Universe is constant. Before going into the detailed uses of the LCE (as we shall in the next section), it will be interesting to look briefly at an example of the interaction of science and other cultural trends of the time.

Nature Philosophy

A year before Joule's remark, Julius Robert Mayer, a German physician, had also proposed a general law of conservation of energy. Mayer had done no quantitative experiments; but he had observed body processes involving heat and respiration. He had also used other scientists' published data on the thermal properties of air to calculate the mechanical equivalent of heat, obtaining about the same value that Joule had.

Mayer had been influenced by the German philosophical school now known as *Naturphilosophie* or "Nature Philosophy." This school, related to the Romantic movement, flourished during the late eighteenth and early nineteenth centuries. According to Nature Philosophy, the various phenomena and forces of nature—such as gravity, electricity, and magnetism—are not really separate from one another but are all manifestations of some unifying "basic" natural force. This philosophy therefore encouraged experiments searching for that underlying force and for connections between different kinds of forces observed in nature.

FIGURE 6.16 Friedrich von Schelling (1775–1854), one of the founders of German *Naturphilosophie*.

The most influential thinkers of the school of Nature Philosophers were Johann Wolfgang von Goethe and Friedrich Wilhelm Joseph von Schelling. Neither of these men is known today as a scientist, although Goethe did write extensively on geology and botany, and did develop a theory of colors that differed from Newton's. Goethe is generally considered Germany's greatest poet and dramatist, while Schelling was a philosopher. Both men had great influence on the generation of European scientists educated in the first decades of the nineteenth century.

The Nature Philosophers were closely associated with the Romantic movement in literature, art, and music. As noted Section 6.2 and in Chapter 4, the Romantics protested against the idea of the Universe as a great machine, the "Newtonian world machine." This idea seemed to them morally empty and artistically worthless. They refused to believe that the richness of natural phenomena, including human intellect, emotions, and hopes, could be understood as the result of the motions of particles—an opinion which in fact almost no scientists then did, or now do, hold or defend.

The Nature Philosophers claimed that nature could be understood as it really is only by direct observation, or "experience." No complicated, "artificial" apparatus must be used, only the senses, feelings, and intuitions. For Goethe the goal of his philosophy was "that I may detect the inmost force which binds the world, and guides its course."

Although its emphasis on the unity of nature led followers of Nature Philosophy to some very useful insights—such as the general concept of the conservation of energy—its romantic and antiscientific bias made it less and less influential. Scientists who had previously been influenced by it, including Mayer, now strongly opposed it. In fact, some hard-headed scientists at first doubted the law of conservation of energy simply because of their distrust of Nature Philosophy. For example, William Barton Rogers, founder of the Massachusetts Institute of Technology, wrote in 1858:

> To me it seems as if many of those who are discussing this question of the conservation of force [we would now call it energy] are plunging into the fog of mysticism.

However, the law was so quickly and successfully put to use in physics that its philosophical origins were soon forgotten. Yet, this episode is a reminder of a familiar lesson: In the ordinary day-to-day work of physical scientists, experiment and mathematical theory are the usual guides. But in making a truly major advance in science, philosophical speculation may also play an important role.

Mayer and Joule were only two of at least a dozen people who, between 1832 and 1854, proposed in some form the idea that energy is conserved.

Some expressed the idea vaguely; others expressed it quite clearly. Some arrived at the belief mainly through philosophy; others from a practical concern with engines and machines or from laboratory investigations; still others from a combination of factors. Many, including Mayer and Joule, worked quite independently of one another. The idea of energy conservation was somehow "in the air," leading to essentially simultaneous, separate discoveries.

The initial wide acceptance of the LCE owed much to the long-range influence of a paper published in 1847, 2 years before Joule published the results of his most precise experiments. The author, a young German physician and physicist named Hermann von Helmholtz, entitled his work "On the Conservation of Force." Helmholtz (using "force" in the modern sense of "energy"), boldly asserted the idea that others were only vaguely expressing, namely, "that it is impossible to create a lasting motive force out of nothing." He restated this theme even more clearly many years later in one of his popular lectures:

> We arrive at the conclusion that Nature as a whole possesses a store of force [energy] which cannot in any way be either increased or diminished, and that, therefore, the quantity of force in Nature is

FIGURE 6.17 Hermann von Helmholtz (1821–1894).

> just as eternal and unalterable as the quantity of matter. Expressed in this form, I have named the general law "The Principle of the Conservation of Force."

Any machine or engine that does work (provides energy) can do so only by drawing from some source of energy. The machine cannot supply more energy than it obtains from the source. When the source runs out, the machine will stop working. Machines and engines can only *transform* energy; they cannot create it or destroy it.

6.6 THE TWO LAWS OF THERMODYNAMICS

Two laws summarize many of the ideas in this chapter. Both of these laws are called laws of thermodynamics. They may be stated in completely analogous fashion as statements of impossibility.

The First Law

The first law of thermodynamics is a general statement of the conservation of energy in thermal processes. It is based on Joule's finding that heat and energy are equivalent. It would be pleasingly simple to call heat "internal" energy associated with temperature. We could then add heat to the potential and kinetic energies of a system, and call this sum the total energy that is conserved. In fact, this solution works well for a great variety of phenomena, including the experiments of Joule. Difficulties arise with the idea of the heat "content" of a system. For example, when a solid is heated to its melting point, further heat input causes melting *but without increasing the temperature*. Simply regarding heat energy measured by a rise in temperature as a part of a system's total energy will not give a complete general law.

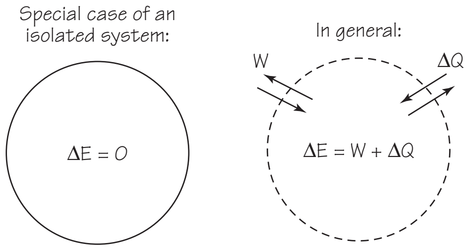


FIGURE 6.18 Diagram of a thermodynamic system.

Instead of "heat," we can use the idea of an *internal energy*—energy in the system that may take forms not directly related to temperature. We can then use the word "heat" to refer only to a *transfer* of energy between a system and its surroundings. (In a similar way, the term *work* is not used to describe something contained in the system. Rather, it describes the transfer of energy from one system to another.)

Even these definitions do not permit a simple statement such as "Heat input to a system increases its internal energy, and work done on a system increases its mechanical energy." Heat input to a system can have effects other than increasing internal energy. In a steam engine, for example, heat input increases the mechanical energy of the piston. Similarly, *work* done on a system can have effects other than increasing mechanical energy. In rubbing your hands together on a cold day, for example, the work you do increases the internal energy of the skin of your hands. In short, a general conservation law of energy must include *both* work *and* heat transfer. Further, it must deal with change in the *total energy* of a system, not with a "mechanical" part and an "internal" part.

In an isolated system, that is, a system that does not exchange energy with its surroundings, the total energy must remain constant. If the system exchanges energy with its surroundings, it can do so in only one of two ways: Work can be done on or by the system, or heat can be passed to or from the system. In the latter case, the change in energy of the system must equal the net energy gained or lost by the surroundings. More precisely, let W stand for the *work* done on or by the system (such as the cylinder in a steam engine). If the work is done by the system, W will be positive; if the work is done on the system, W will be negative. Similarly, let ΔQ represent the net *heat transfer* to or from the system. If the net heat transfer is to the system, ΔQ will be positive; if the net transfer is from the system, ΔQ will be negative.

With these definitions, *the first law of thermodynamics states that the change in the total energy of the system*, ΔE, *is given by the sum of the work done on or by the system and the net heat transfer to or from the system*, *or in symbols*

$$\Delta E = W + \Delta Q.$$

This general expression includes as special cases the preliminary versions of the energy-conservation law given earlier in the chapter. If there is no heat transfer at all, then $\Delta Q = 0$, and so $\Delta E = W$. In this case, the change in energy of a system equals the work done on or by it. On the other hand, if work is done neither on nor by a system, then $W = 0$, and $\Delta E = \Delta Q$. Here the change in energy of a system is equal to the net heat transfer.

The equation above is enormously useful. But we still need a description of that part of the total energy of a system called "heat" (or better, "internal" energy). So far, we have seen only that an increase in internal energy is sometimes associated with an increase in temperature. We also mentioned the long-held suspicion that internal energy involves the motion of the "small parts" of bodies. We will take up this problem in detail in the next chapter.

The Second Law

The second law of thermodynamics is a general statement of the limits of the heat engine and is based on Carnot's work. We indicated in Section 6.4 that a reversible engine is the most efficient engine. Any other engine is not as efficient. In order to formulate that idea generally and precisely, a new concept, *entropy*, must be introduced.

The change in entropy of a system, ΔS, is defined as the net heat, ΔQ, gained or lost by the system, divided by the temperature (in Kelvin) of the system, T:

$$\Delta S = \frac{\Delta Q}{T}.$$

This equation defines only changes of entropy, S, rather than the absolute value of entropy. But this is similar to what we encountered in defining potential energy. In both cases what interests us is only the *change*. Once a standard state for the system for which $S = 0$ is chosen, the total entropy for any state of the system can be determined.

We introduced the concept of an ideal, reversible engine in Section 6.4. Such an engine, working in a cycle between hot and cold bodies (as any heat engine does), must have the same entropy at the end of a cycle as it does at the start. This is because, at the end of the cycle, T is back to its initial value, and as much heat and work energy as has been given up in one part of the cycle as has been gained in the rest of the cycle; so ΔQ on the whole during the entire cycle is zero. Since the change of entropy is defined as $\Delta S = \Delta Q/T$, the change in entropy during one cycle is also zero, $\Delta S = 0$.

What about an engine that is not reversible and thus less than ideal, such as an actual steam engine? You know it must be less efficient than a perfectly reversible engine, which would have 100% efficiency. So, for such an engine, the heat transfers must be greater than those for an ideal engine.

At the end of each work cycle, ΔQ within the engine will not be zero but positive, and ΔS, correspondingly, will have a positive value. In short, though the total energy inside and outside the engine will, by the first law, be unchanged, the *entropy* of the system will have *increased*. Note that this will happen again and again as this or any other engine of this sort repeats its work cycle. So the result is that the entropy of the universe will constantly increase while the less-than-ideal engine is running.

We can summarize our results for the change in entropy of the universe resulting from the operation of simple heat engines as follows:

$$\Delta S_{\text{universe}} = 0 \quad \text{(reversible processes)},$$

$$\Delta S_{\text{universe}} > 0 \quad \text{(any other process)}.$$

Although proven here only for these simple heat engines, these results are general ones. In fact, these apply to all thermal processes. For simplicity, these two expressions may be joined together by using the greater than or equal to sign, $\geqq$ or more simply $\geq$:

$$\Delta S_{\text{universe}} \geq 0,$$

where the = sign refers to reversible processes; the > sign refers to any other process. *The last expression is, in fact, a mathematical formulation expressing the second law of thermodynamics.*

Rudolf Clausius, who first formulated the second law in the form given here, paraphrased the two laws of thermodynamics in 1850, as follows: "*The energy of the Universe remains constant, but its entropy seeks to reach a maximum.*"

THE "THIRD" LAW

Some physicists include a third law among the laws of thermodynamics. The third law states that no system can be cooled to absolute zero.

If we include the third law, a lighthearted synopsis of the three laws is:

1. you cannot win; you can only break even;
2. you can break even only at absolute zero;
3. you cannot reach absolute zero.

6.7 FAITH IN THE LAWS OF THERMODYNAMICS

For over a century, the law of conservation of energy has stood as one of the most fundamental laws of science. You will encounter it again and again in this course, in studying electricity and magnetism, the structure of the atom, and nuclear physics. Throughout the other sciences, from chemistry to biology, and throughout engineering studies, the same law applies. Indeed, no other law so clearly brings together the various scientific fields, giving all natural scientists and engineers a common set of concepts.

The law of conservation of energy has been immensely successful. It is so firmly believed that it seems almost impossible that any new discovery could disprove it. However, in some experiments, energy does seem to appear or disappear in a system, without being accounted for by changes in known forms of energy. For instance, as heat is added to a melting ice cube, the temperature of the ice cube does not increase. In such cases, physicists preferred to assume that the added heat takes the form of a kind of energy not yet investigated, rather than to consider seriously the possibility that energy is not conserved. The German philosopher Leibniz once proposed that energy could be dissipated among "the small parts" of bodies. He advanced this idea specifically in order to maintain the principle of conservation of energy in inelastic collisions and frictional processes. Leibniz's faith in energy conservation was justified. Other evidence showed that "internal energy," stored by the motion of submicroscopic particles in the material being experimented on, changed by just the right amount to explain observed changes in external energy, such as the case of a melting ice cube.

Another similar example is the "invention" of the neutrino by the physicist Wolfgang Pauli in 1930. Experiments had suggested that energy disappeared in certain nuclear reactions. Pauli proposed that a previously unsuspected and then undetectable subatomic particle, which Enrico Fermi named the "neutrino," was produced in these reactions. He proposed that the neutrino carried off some of the energy. Physicists accepted the neutrino theory for more than 20 years even though neutrinos by themselves could not be shown to exist. Finally, in 1956, neutrinos were indeed detected, in experiments using the radiation from a nuclear reactor. (The experiment could not have been done in 1930, since no nuclear reactor existed until over a decade later.) Again, faith in the law of conservation of energy turned out to be justified.

The theme of "conservation" is so powerful in science that scientists believe it will always be justified. Any apparent exceptions to the law will sooner or later be understood in a way which does not require us to give up the law. At most, these exceptions may lead us to discover new forms of matter or energy, making the law even more general and powerful.

The French mathematician and philosopher Henri Poincaré expressed this idea in 1903 in his book *Science and Hypothesis:*

> . . . the principle of conservation of energy signifies simply that there is *something* which remains constant. Indeed, no matter what new notions future experiences will give us of the world, we are sure in advance that there will be something which will remain constant, and which we shall be able to call *energy.*

Today, it is agreed that the discoveries of various conservation laws with cosmic reach we have discussed (and others to be mentioned later) were among the most important achievements of science. These laws are powerful and valuable tools of analysis. All of them basically affirm that, whatever happens within a system of interacting bodies, certain measurable quantities will remain constant as long as the system remains isolated.

The list of known conservation laws has grown in recent years. The area of fundamental (or "elementary") particles has yielded much of this new knowledge. Some of the newer laws are imperfectly and incompletely understood. Others are on uncertain ground and are still being argued. Below is a list of conservation laws to date. This list is not complete or eternal, but it does include the conservation laws that make up the working tool-kit of physicists today.

Conservation Laws

1. Linear momentum.
2. Angular momentum (including spin).
3. Energy (including mass).
4. Electric charge.
5. Electron-family number.
6. Muon-family number.
7. Baryon-family number.
8. Strangeness number.
9. Isotopic spin.

Number 3 is a generalized form of the first law of thermodynamics; the inclusion of mass will be explained in the chapter on relativity theory. Numbers 4–9 result from work in nuclear physics, high-energy physics, or elementary or fundamental particle physics.

The Status of the Second Law

The second law of thermodynamics has a status rather different from the conservation laws. It, too, is extremely successful and powerful. It, too, has continued to stand as one of the fundamental laws of science. Unlike the conservation laws or Newton's laws of motion, the second law of thermodynamics is less concerned with giving precisely measurable results than with saying that certain processes or phenomena are impossible. For example, it is impossible to make the entropy of the Universe (or of an isolated system) decrease; it is impossible to make heat flow from a cold body to a hot one without doing work on something; it is impossible to invent a heat engine with efficiency greater than 100%. In other words, the processes involving heat happen in one direction only: The entropy increases; heat flows from hot objects to cold ones. Thus, the second law is connected in some fundamental way with the notion that time proceeds in one direction only. To word it differently, when a movie taken of real events is run backward, what you see cannot, in detail, be found to occur in the real world. For example, while two liquids can quickly mix together by themselves; they cannot spontaneously un-mix themselves. These ideas will be examined in more detail in the next chapter.

The second law states that during reversible processes—such as those involving ideal, frictionless heat engines—the entropy of the Universe will remain constant. However, all other processes, all of which would not be reversible—that is, they are *irreversible*—the entropy of the Universe would increase. In no case will the net entropy of the Universe decrease. For example, as the second law requires, heat will not flow by itself from cold bodies to hot bodies, because that would involve a decrease in entropy. A ball lying on the floor will not somehow gather energy from its surroundings and suddenly leap up. An egg will not unscramble itself. An ocean liner cannot be powered by an engine that takes heat from the ocean water and ejects ice cubes. All these and many other events could occur without violating any principles of Newtonian mechanics, including the law of conservation of energy. But they do not happen; they are "forbidden" by the second law of thermodynamics. (They are "forbidden" in the sense that such things do not happen in nature.)

All familiar processes are to some degree irreversible, and thus contribute to an increase in the entropy of the Universe. As this happens, the usefulness of the heat available for work in engines will decline. Lord Kelvin predicted that eventually all bodies in the Universe would reach the same temperature by exchanging heat with one another. When this happened, it would be impossible to produce any useful work from heat, since work can only be done by means of heat engines when heat flows from a hot body

FIGURE 6.19 An illustration of the “heat death” of the universe, from Camille Flammarion’s 1893 book: *La Fin du Monde (The End of the World)*.

to a colder body. Finally, the Sun and other stars would cool, all life on Earth would cease, and the Universe would be dead.

This idea of a “heat-death” of the Universe, based on predictions from thermodynamics, aroused some popular interest at the end of the nineteenth century. The idea later appeared in several books, such as H.G. Wells’ *The Time Machine*, and in Isaac Asimov’s short story “The Last Question.”

SOME NEW IDEAS AND CONCEPTS

absolute temperature scale
absolute zero
caloric fluid
calorie
Calorie
Carnot’s finding
condenser
cycle
cylinder
efficiency
entropy
feedback
governor
heat-death of the Universe
law of conservation of energy (LCE)
mechanical equivalent of heat
Nature Philosophy (*Naturphilosophie*)
power
reversible engine
specific heat
thermodynamics, first law
thermodynamics, second law

SOME IMPORTANT EQUATIONS

$$Q = mc\,\Delta T,$$

$$\text{eff} = \frac{\text{useful } E_{\text{out}}}{E_{\text{in}}},$$

$$P = \frac{E}{t},$$

$$\Delta E = W + \Delta Q,$$

$$\Delta S_{\text{universe}} \geq 0,$$

$$\Delta S = \frac{\Delta Q}{T}.$$

DEFINITIONS OF IMPORTANT UNITS

1 W = 1 J/s,

T (K) = t (°C) + 273.

STUDY GUIDE QUESTIONS

6.1 Heat as a Form of Energy

1. When a book slides to a stop on the horizontal rough surface of a table:
   (a) the kinetic energy of the book is transformed into potential energy;
   (b) heat is transformed into mechanical energy;
   (c) the kinetic energy of the book is transformed into heat energy;
   (d) the momentum of the book is conserved.
2. The kilocalorie is:
   (a) a unit of temperature;
   (b) a unit of energy;
   (c) 1 kg of water at 1°C.
3. In Joule's paddle-wheel experiment, was all the change of gravitational potential energy used to heat the water?
4. How are heat and temperature related to each other?
5. How are heat and mechanical energy related to each other?

6.2 The Steam Engine and the Industrial Revolution

1. Describe in your own words, possibly with a drawing, the operation of Watt's steam engine.
2. The purpose of the separate condenser in Watt's steam engine is to:
   (a) save the water so it can be used again;
   (b) save fuel by not having to reheat the cylinder after cooling;
   (c) keep the steam pressure as low as possible;
   (d) make the engine more compact.
3. The history of the steam engine suggests that the social and economic effects of technology are:
   (a) always beneficial to everyone;
   (b) mostly undesirable;
   (c) unimportant one way or another;
   (d) none of the above.

6.3 Power and Efficiency of Engines

1. A strong horse, working steadily, is able to lift a 75-kg mass at a speed of 1 m/s. What is the power output of the horse in watts?
2. During a certain period, a home consumes 1 kW-hr of energy. How many joules is this? How long could this amount of energy light a 100-W light bulb?
3. The efficiency of a heat engine is the ratio of:
   (a) the work output to the heat input;
   (b) the work output to the heat output;
   (c) the heat output to the heat input.
4. What would be the efficiency, in percent, of a steam engine that took in the equivalent of 3000 J of heat and produced 1200 J of work?

6.4 Carnot and the Beginnings of Thermodynamics

1. What does Carnot's finding say about the efficiency of heat engines?
2. A heat engine is most efficient when it works between objects that have:
   (a) a large temperature difference;
   (b) a small temperature difference;
   (c) a large size.
3. In what way is a refrigerator or an air conditioner also a heat engine?
4. How are the Kelvin and Celsius temperature scales related to each other? What would be the temperatures of freezing water, boiling water, and absolute zero on these two scales?

6.5 Arriving at a General Conservation Law

1. The significance of German Nature Philosophy in the history of science was that it:
   (a) was the most extreme form of the mechanistic viewpoint;
   (b) was a reaction against excessive speculation;

   - (c) stimulated speculation about the unity of natural phenomena;
   - (d) delayed progress in science by opposing Newtonian mechanics.
2. Discoveries in electricity and magnetism early in the nineteenth century contributed to the discovery of the law of conservation of energy because:
   - (a) they attracted attention to the transformation of energy from one form to another;
   - (b) they made it possible to produce more energy at less cost;
   - (c) they revealed what happened to the energy that was apparently lost in steam engines;
   - (d) they made it possible to transmit energy over long distances.
3. The development of steam engines helped the discovery of the law of conservation of energy because:
   - (a) steam engines produced a large amount of energy;
   - (b) the caloric theory could not explain how steam engines worked;
   - (c) the precise idea of work was developed to rate steam engines;
   - (d) the internal energy of a steam engine was always found to be conserved.

6.6 The Two Laws of Thermodynamics

1. Define the meaning of the symbols ΔE, ΔQ, W, and ΔS for a system.
2. State the first law of thermodynamics in your own words.
3. What is the difference between the first law and the law for energy conservation?
4. The value of ΔQ can be positive, negative, or zero. Using an example, such as the steam engine cylinder, explain what is happening in each case and exactly why ΔQ is positive, negative, or zero.
5. Give an example of an imaginable situation that would violate the law regarding entropy increase.
6. The first law of thermodynamics is:
   - (a) true only for steam engines;
   - (b) true only when there is no friction;
   - (c) a completely general statement of conservation of energy;
   - (d) the only way to express conservation of energy.
7. What two ways are there for changing the total energy of a system?
8. The second law of thermodynamics says that the entropy of the Universe:
   - (a) cannot increase;
   - (b) cannot decrease;
   - (c) must increase;
   - (d) must decrease.
9. The presumed “heat-death of the Universe” refers to a state in which:
   - (a) all mechanical energy has been transformed into heat energy;
   - (b) all heat energy has been transformed into other forms of energy;
   - (c) the temperature of the Universe decreases to absolute zero;
   - (d) the supply of coal and oil has been used up.

6.7 Faith in the Laws of Thermodynamics

1. Give some examples of situations in which energy seems not to be conserved.
2. How was the law of energy conservation confirmed in the situations in 1?
3. How does the status of the second law of thermodynamics differ from that of the conservation laws?
4. How might the second law of thermodynamics be connected with the forward motion of time?
5. What is meant by the "heat-death" of the universe?

DISCOVERY QUESTIONS

1. The introduction of steam technology transformed the economic and social lives of people in the industrial world. In what ways has the introduction of computer technology changed our economic and social lives?
2. Give some examples of the first and second laws of thermodynamics in actual cases.
3. Give an example of a hypothetical situation in which the first law of thermodynamics would not be violated but the second law is.
4. Give an example of a hypothetical situation in which the second law of thermodynamics would not be violated but the first law is.
5. What is the difference between work and power?
6. Suppose the temperatures of the "hot" and "cold" bodies in a heat engine were the same. What would be the efficiency of a heat engine that attempted to operate between these two bodies? What would be the work output?
7. The introduction of the steam engine had both positive and negative effects, although all of these effects were not predicted at the time.
   (a) List several *actual* effects on society, both beneficial and undesirable ones, of the steam engine and of the gasoline internal combustion engine.
   (b) List several *predicted* effects of nuclear power and of solar power by its inventors and the general public at the time of its invention. List both beneficial and undesirable ones.
8. Explain why all ideal reversible engines have the same efficiency and why this efficiency is the maximum possible for an engine. What is an ideal engine? What is a reversible engine?
9. Assuming that no real engine can be perfectly reversible, why does the formula for the maximum efficiency of an engine imply that absolute zero can never be reached in practice?
10. Any of the terms in the equation $\Delta E = W + \Delta Q$ can have negative values.
    (a) What would be true of a system for which:
        (1) ΔE is negative?
        (2) ΔQ is negative?
        (3) W is negative?

(b) Which terms would be negative for the following systems?
  (1) a person digging a ditch;
  (2) a car battery while starting a car;
  (3) an electric light bulb just after it is turned on;
  (4) an electric light bulb an hour after it is turned on;
  (5) a running refrigerator;
  (6) an exploding firecracker.

11. In each of the following, trace the chain of energy transformations from the Sun to the energy in its final form.
    (a) A pot of water is boiled on an electric stove.
    (b) An automobile accelerates from rest on a level road, climbs a hill at constant speed, and comes to a stop at a traffic light.
    (c) A windmill pumps water out of a flooded field.
12. Why is it that despite centuries of attempts no perpetual motion machine has been constructed? Is it likely that one will be in the future?
13. Why can a block of ice at 0°C and water at 0°C coexist in an insulated bucket without changes either way in the amount of ice?
14. Why can an ocean liner not run all its engines simply by drawing heat from the ocean, thereby making the ocean a bit colder?
15. Since there is a tendency for heat to flow from hot to cold, will the Universe eventually reach absolute zero?

Quantitative

1. You walk up a flight of stairs to the second floor, which is 10 m above the first floor, in 15 s. At the same time, a friend runs up the stairs in 5 s. Both of you weigh 80 N. Find the amount of work and the amount of power that each of you exerts in getting up the stairs.
2. A skier of 70-kg mass experiences a pull on a ski lift from an engine transmitting 140 W to the cable. Neglecting friction, how high can the engine pull the skier in 500 s?
3. One hundred joules (100 J) of heat is put into two engines. Engine A can lift 5 N a distance of 10 m in 10 s. Engine B pulls with a force of 2 N for 5 s a distance of 20 m. Calculate the efficiency and power of each engine.
4. While traveling in Switzerland on his honeymoon, James Prescott Joule attempted to measure the difference in temperature of the water at the top and at the bottom of a waterfall. Assuming that the amount of heat produced in the water when it is stopped at the bottom is equal to the decrease in its gravitational potential energy, calculate roughly the temperature difference you would expect to observe between the top and bottom of Niagara Falls, which is 50 m in height. Does it matter how much water goes down the waterfall?
5. If you place a hot body and a cold one in thermal contact, heat will flow from the first to the second spontaneously. Suppose an amount of heat Q flows from a body at temperature T_1 to a body at T_2. What is the entropy change of the universe?

6. An ice cube (10 g) at 0°C melts in a glass of water (100 g) at a temperature just above 0°C. Melting the ice requires 3.4 × 106 J of energy (which comes from cooling the water). Neglecting temperature changes, what is the entropy change of the ice? of the water? of the universe?
7. In Section 6.3 you saw that a 100-W light bulb burning for 10 hr consumes 1 kWhr of energy. The production of 1 kWhr of electricity to run the light bulb requires the burning of about 0.8 lb of coal in an electric generating plant.
   (a) If the average citizen consumes energy at the rate of 1.5 kJ/s, how many pounds of coal do you consume per year? during an expected life span of 75 yr?
   (b) The United States population is about 280 million. For their energy needs, how many pounds of coal would they consume in 1 day?
8. On average, a person emits as much heat from his/her body as a 100-watt bulb. How come?