4 Energy

WHAT IS ENERGY?

Energy is one of the most important concepts in science. It appears in many forms, including mechanical energy, thermal energy, electromagnetic energy, chemical energy, and nuclear energy. Wherever and whenever anything happens, like the explosion of a distant sun or the falling of a golden leaf from a tree in autumn, a change in some form of energy is involved. In spite of our familiarity with the concept of energy, few of us can define it properly. What is energy? Can we measure it? Can we touch it?

Energy is an abstract concept introduced by physicists in order to better understand how nature operates. Since it is an abstract idea, we cannot form a concrete picture of it in our minds, and we find it very difficult to define it in simple terms. But we can perhaps understand what it can do. Energy is the ability to do work. Therefore, before we can fully understand what this definition of energy means, we need to know what we mean in physics by work, a word that we use in our everyday language.

THE CONCEPT OF WORK

Work involves an effort directed toward the production of something. In physics, what we understand for work differs somewhat from our everyday meaning of the word, and we must be careful to distinguish between the two meanings. A few examples should illustrate what work means in physics. Suppose your car's battery dies and you decide to push the car to the gas station 500 feet along the road. When you push the car, you exert a force on it, even if the car does not move. However, if the car begins to move as you push it, then you are doing work on it. The man pushing the stalled car (Figure 4.1a) performs work only if he is able to move it through some distance. If he attempts to push a bulldozer, he probably will not be able to move it. In this case, the work done is zero, even if the man gets very tired (Figure 4.1b).

Suppose now that a child is pulling a wagon (Figure 4.2a). The wagon rolls along the horizontal surface of the sidewalk as the child pulls on the handle. We know from our own experience that if the direction in which the handle is pulled is too close to the vertical, the child's effort to move the wagon is not as effective. If the wagon is extremely heavy, the child must lean forward and pull on the handle in a horizontal direction. In fact, the horizontal direction makes the force most effective in this case (although this position is probably uncomfortable for the child; as seen in Figure 4.2b). If the child were to pull on the wagon in a direction perpendicular to the direction of

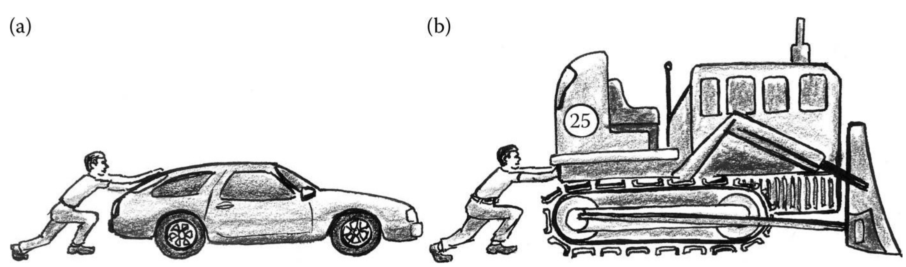

FIGURE 4.1 (a) Work is done when the force applied by the man pushing makes the car move some distance. (b) The man pushing the bulldozer will not be able to move it. In this case, he performs no work on the bulldozer.

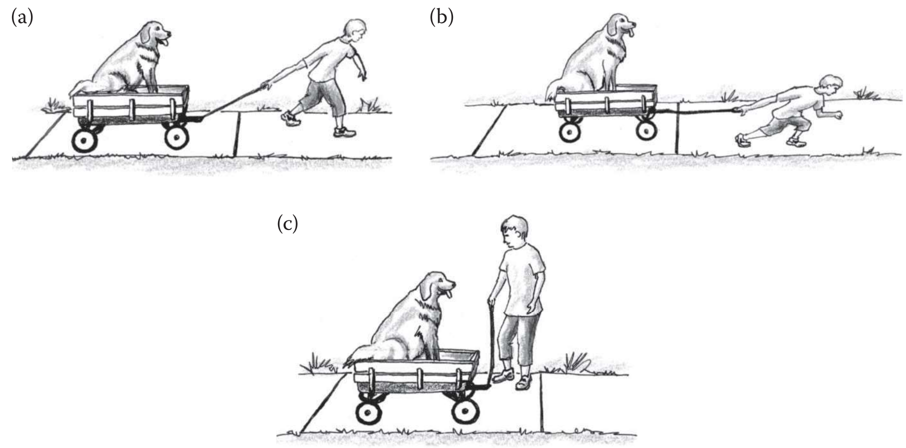

FIGURE 4.2 (a) Pulling a moderately heavy wagon. (b) To pull effectively on an extremely heavy wagon, the child must lean forward and pull in a horizontal direction. (c) Pulling the strap in a vertical direction makes it impossible to move the wagon.

motion (Figure 4.2c), his effort would be wasted; the force that he would apply in this case would do nothing for the motion of the wagon along the floor.

If the child pulls with the same force in all cases described in the previous situation, the work done on the wagon will be maximum when the applied force is in the direction of motion of the wagon, zero when the force is at right angles to the direction of motion, and an intermediate value when the force is along any other direction. The closer the applied force gets to the direction of motion, the more effective it becomes in producing work. We can say that work is a measure of the productivity of a force. For the simple case of a constant force acting on an object along the direction of motion of the object, as in Figures 4.2b and 4.3, the work done on the object is the product of the force and the distance the object moves, or

$$\text{Work} = \text{force} \times \text{distance or } W = F \times d.$$

FIGURE 4.3 The force exerted by the horse is in the same direction as that of the resultant motion. In this case, the work done by the horse is equal to the product of the magnitude of the force and the distance traveled.

When the applied force is not along the direction of motion, the force can be resolved into two components: one parallel to the direction of motion, and the other perpendicular to it. As we saw from our discussion, only the parallel component does work.

It is interesting to notice that if a person walks on a horizontal surface at a steady pace while carrying a suitcase, the force that he exerts on the suitcase to prevent it from falling to the ground does not produce work on the suitcase. However, if the suitcase is heavy and the person has to walk a long distance, he begins to sweat. Why should he sweat if he is doing no work? Even if he is standing still while holding the suitcase, he will get tired. The fact is that in this case, there actually is motion inside the man's arm and work is being done on the muscle fibers. While the man is holding the suitcase, nerve impulses are continuously reaching the muscles in his arm. When these nerve impulses reach a muscle fiber, the fiber lurches for an instant and then relaxes. At any one time, large numbers of fibers are tightening up, while the rest are relaxing. Since we were analyzing the motion of the suitcase held by the man, a situation external to the activity of the muscle fibers inside the man's arm, we concluded correctly that no work was done on the suitcase.

UNITS OF WORK AND ENERGY

The SI unit of energy (and work, since energy is the ability to do work and thus must have the same units) is the *joule* (J). This unit is named in honor of the English physicist James Prescott Joule (1818–1889) whose work clarified the concepts of work and energy. A joule combines the units of force and distance:

$$1\,\text{J} = 1\,\text{Nm}.$$

We can illustrate this unit with two examples. It requires about 1 J of work to lift a baseball from the ground to your chest, whereas it takes about 10 J of energy to pick up an average physics textbook from the bottom shelf of a bookcase and stand up to read it.

When dealing with the energies of atoms or electrons, though, the joule is too large a unit. For these purposes, another unit, the electron volt (eV), is used. The conversion factor between electron volts and joules is

$$1\,\text{eV} = 1.602 \times 10^{-19}\,\text{J}.$$

A frequently used multiple of the eV is the MeV, which equals one million eV.

THE CONCEPT OF ENERGY

The concept of work is very useful in understanding the concept of energy. As we stated at the beginning of this chapter, energy is the capacity to do work; that is, energy allows us to perform tasks, to do work. We can also think of energy as the result of doing work. It is the chemical energy stored in the man's body in Figure 4.4 that enables him to do the work on the car as he pushes it,

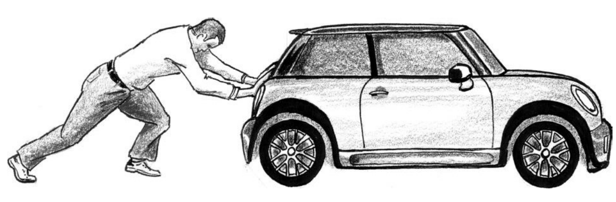

FIGURE 4.4 Energy is the capacity to do work. The chemical energy in the man's body enables him to do work on the car.

converting chemical energy into energy of motion of the car and into heat (thermal energy) as the tires rub against the pavement.

This idea of energy as something stored that can do work was called first *vis viva* (Latin for "living force") by the German philosopher Gottfried W. Leibniz (1646–1716), because he thought that only living things could have the capacity to do work. The English scientist Thomas Young (1773–1829) realized that inanimate objects, like the wind, can do work—by moving a windmill or a ship, for example. He proposed the name *energy*, a name he fashioned from Greek words meaning "work within," for this work stored in bodies.

Of the various types of energy listed at the beginning of this chapter, we will only consider mechanical energy for the moment. Later in this book, most of the other kinds of energy will be studied in some detail. An object may have mechanical energy by virtue of its state of motion, its location in space, or its internal structure.

PIONEERS OF PHYSICS: JAMES PRESCOTT JOULE

James Joule, the second son of a wealthy brewer, had a good early education. As a young man, he was taught by the renowned chemist John Dalton and showed a talent for science. At 19, he did several experiments investigating the nature of electromagnets, which resulted in a published paper.

Born in 1818 near Manchester, England, Joule developed an early interest for the machines in his father's large brewery. This interest made him proficient at designing experiments and building the machines required to run them. He soon developed an almost fanatical zeal for accurate measurements. Such was his dedication that he even took time during his honeymoon to design a special thermometer with which to measure the temperature difference between the top and the bottom of a waterfall that he and his bride visited.

When Joule was 15, his father became ill and retired. Although the young James had to spend time running the brewery, he continued his scientific endeavors. At 22, he calculated the amount of energy produced by an electric current and went on to spend the next 10 years devising experiments to measure energy in every conceivable way.

The initial report of his experiments was met with skepticism and even rejection. The Royal Society did not accept his original paper, and Joule was forced to present his results at a public lecture. His report was finally published in the *Manchester* newspaper at the instigation of his brother, who was the paper's music critic (Cardwell 1989).

Eventually, his work caught the attention of other scientists and Joule gained the recognition he deserved. He was elected to the Royal Society in 1850, and years later, he became the president of the British Association for the Advancement of Science. In 1854, his wife died after only 6 years of marriage and Joule, deeply distressed, retreated to his work. In 1875, he began to have financial difficulties and Queen Victoria granted him a pension. Toward the end of his life, he became concerned and disturbed about the applications of his work to warfare. He died in 1889, at the age of 71, after a long illness.

ENERGY OF MOTION

As we have seen, work involves forces and motion. An object in motion has the capacity to do work: Running water can turn a millstone, a gusty wind sets a windmill in motion and drives a sailing ship, and a truck ramming into the rear of a small car at a traffic light will surely move it some distance!

Thus, an *object in motion* has energy. It is the motion of the object that causes it to contain energy. Still water does not turn a millstone, and still air does not drive a sailing ship. We call the energy of an object in motion *kinetic energy.* The word *kinetic* was first introduced by the English physicist Lord Kelvin in 1856 and comes from a Greek word that means motion. The amount of kinetic energy that an object has depends on its mass and its speed. Thus, a large truck traveling at the same speed as a small sports car would have more kinetic energy due to its larger mass. Likewise, a runner would have more kinetic energy than a person of similar weight walking along the same path, due to the runner's greater speed.

Kinetic energy—the energy that an object has by virtue of its motion—is thus proportional to the mass of the object and to its speed. It is equal to one-half the product of the mass m and the square of the speed v^2:

$$\text{Kinetic energy (KE)} = \frac{1}{2}mv^2.$$

ENERGY OF POSITION

A snowball at rest at the top of a hill has no kinetic energy since it is not moving. However, it is *potentially* capable of doing work on a snowman at the bottom of the cliff, if it is set into motion by the boy (Figure 4.5). This type of energy, which we call *gravitational potential energy*, is due to the object's separation from the earth. It is called *gravitational* because the gravitational force of attraction of the earth does work on the object as it falls toward the ground, and it is called *potential* because energy has been stored for later use. Notice that unless the boy pushes it, the snowball will not reach the ground below where it can harm the snowman. If the snowball is never pushed, it will never become separated from the earth, remaining on the ground at the top of the cliff. When it is pushed, it acquires a separation from the earth equal to the height of the cliff. What we call ground, then, is actually the lowest position the object can reach in a particular situation. This lowest position or ground is the *reference level* from which the position of the object is measured. We are free to choose an arbitrary reference level that better suits our particular situation.

The gravitational potential energy depends also on the object's mass. Thus, a tree falling on a house after a storm does much more damage (more work!) than a walnut falling from a tree standing on the roof of the same house. If an object's height changes, so does its potential energy because the distance to the ground increases. If you lift a box full of books from the ground and place it

FIGURE 4.5 The snowball has gravitational potential energy by virtue of its position with respect to the ground. If pushed off the cliff, its potential energy will allow it to do work on the snowman below.

on a chair, the box acquires potential energy because of its height with respect to the ground. This potential energy comes from the work done by your muscles in lifting the box. If you now decide to place the box on the table, the potential energy of the box increases by an amount proportional to the increase in height. The increase in potential energy results from the additional work that you have to do to lift the box from the chair up to the table.

We can summarize the previous discussion as follows:

> Gravitational potential energy is the energy that an object has by virtue of its separation from the earth's surface. Potential energy is proportional to the mass of the object and to the height above an arbitrary reference level.

It is not difficult to obtain the exact expression for the gravitational potential energy. Consider the boy lifting the baseball of mass m in Figure 4.6. The potential energy of the ball before the boy picks it up is zero, if we choose the floor as our reference level. As the boy slowly lifts the ball, the potential energy increases until the ball reaches the table. The work done by the boy in lifting the ball slowly, without acceleration, is equal to the force applied by the boy multiplied by the distance traveled by the ball, which is equal to the height of the table h. The magnitude of the force applied by the boy equals the ball's weight mg. The force is in the same direction as that of the motion. Therefore,

$$W = Fh = mgh.$$

Thus, $W = mgh$ is the work done by the boy on the ball. When the ball is resting on the table, it has no speed and therefore no kinetic energy. It, however, has stored energy by virtue of being at a height h above the floor; in other words, it has stored energy by virtue of being at a distance h above the reference level. If the boy decides to push the ball off the table, it would, of course, fall down and gain kinetic energy, which would have come from the stored energy when it was resting on the table. This stored energy is what we call *potential energy*. We can write for potential energy, then,

$$PE_{grav} = mgh.$$

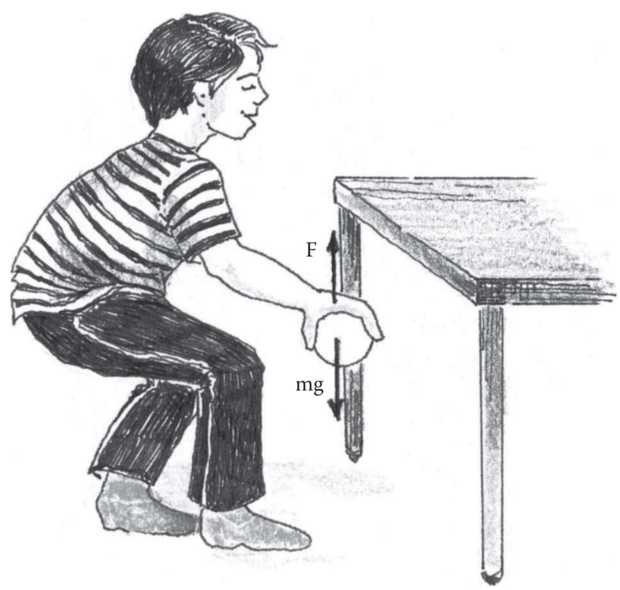

FIGURE 4.6 As the boy slowly lifts the ball, the ball gains gravitational potential energy.

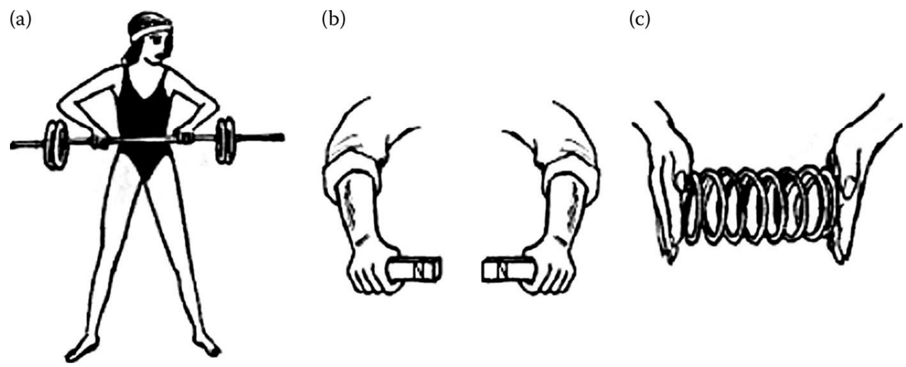

FIGURE 4.7 Different kinds of potential energy. (a) The gravitational potential energy of the weights increases as the weights are lifted. (b) The magnetic potential energy increases as the two magnets are brought closer together with their north poles facing. (c) The elastic potential energy of the spring increases as it is compressed.

There are other kinds of potential energy (Figure 4.7). When we push two magnets together with their north poles facing, there is an increase in *magnetic* potential energy. If you compress a spring by holding it between the palms of your hands and pushing, the *elastic* potential energy of the spring increases.

In all these cases, the potential energy is stored in the entire system of interacting bodies. After we bring the two magnets together, for example, we could hold either one of the two magnets in place and let the other move away. Since either magnet can be released and allowed to move away from the other magnet, making use of the available potential energy, this magnetic potential energy must reside in the system of the two interacting magnets. When we lift a baseball up to a certain height and then release it so that it falls toward the earth, it seems as if the potential energy belongs only to the baseball. However, if we could devise a method to secure the baseball in space with respect to the sun, the earth would "fall" toward the baseball. The gravitational potential energy in this case resides in the earth–baseball system.

ELASTIC POTENTIAL ENERGY

The stretched spring in Figure 4.8 has stored energy. We call this *elastic potential energy*. If we pull on the spring with a force **F**, the increase in length x is proportional to the stretching force (as long as the spring is not stretched too much). We can write for the force exerted by the person pulling on the spring:

$$F = kx,$$

where k is called *the force constant* of the spring. This force law is known as *Hooke's law*. By Newton's third law, the spring exerts an equal and opposite force on the person pulling, or

$$F = -kx.$$

The applied force increases from 0 when the spring is not stretched, to kx when the spring has been stretched a distance x. Thus, the average force is the sum of these two values divided by two, or

$$\bar{F} = \frac{0 + kx}{2} = \frac{1}{2}kx.$$

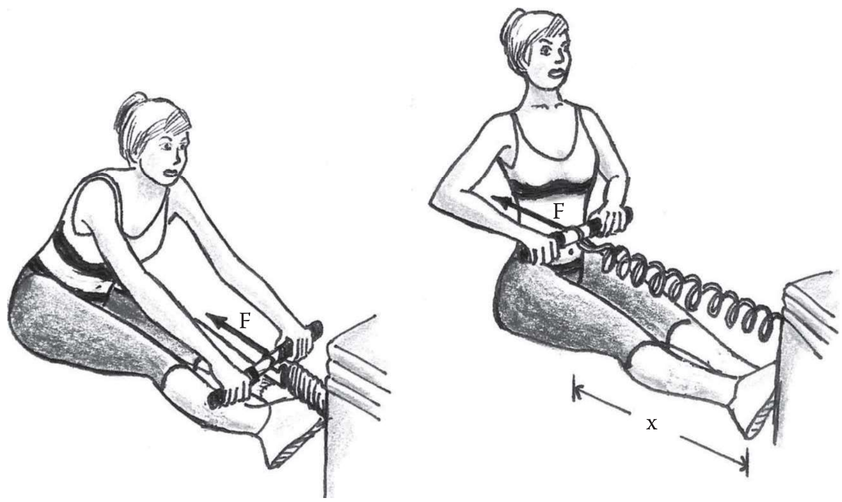

FIGURE 4.8 The spring is stretched from its equilibrium position by a force that is proportional to the displacement *x*.

The work done in stretching the spring from the equilibrium position out to a distance x is the product of this average force F and the displacement x:

$$W = \bar{F}x = \left(\frac{1}{2}kx\right)x = \frac{1}{2}kx^2.$$

This work is converted into elastic potential energy in the spring:

$$\mathrm{PE}_{\mathrm{elastic}} = \frac{1}{2}kx^2.$$

THE WORK–ENERGY THEOREM

When you throw a bowling ball, you do work on it as you push the ball through some distance. The bowling ball gains speed, and its kinetic energy increases. After the ball leaves your hand, it travels along the lane and hits the pins, pushing them down, thereby doing work on them. The kinetic energy that the ball acquired came from the work done on it. The work that the ball does on the pins comes at the expense of some of its kinetic energy: The ball slows down after it hits the pins. In this case, work is being converted into kinetic energy (and some of that kinetic energy is being converted back into work).

We had observed when discussing gravitational energy that the work done by the boy of Figure 4.6 in lifting the ball up to a certain height h was $W = mgh$. The potential energy acquired by the ball when lifted to this height comes from the work that the boy does on it. If the boy lifts the ball without accelerating it, all the work done on the ball is converted into potential energy.

In general, work can be converted into both kinetic and potential energies. This statement is what we call the *work–energy theorem*. When a basketball player shoots a basket, the work done on the ball is changed into an increase in the kinetic energy of the ball, as it accelerates in the player's hands, and into potential energy as the ball gains height.

CONSERVATIVE AND NONCONSERVATIVE FORCES

When we lift an object of mass m, initially at rest on the ground, slowly up to a height h, the work that we do on the object is

$$W = mgh.$$

If the object is a book with a mass of 1 kg and we lift it to a height of 0.5 m, the work done on the book would be $W = 1\ \text{kg} \times 9.8\ \text{m/s}^2 \times 0.5\ \text{m} = 4.9\ \text{J}$. Now, suppose that we pick up the same book from a shelf that is 1 m above the floor and place it on another shelf 1.5 m high (see Figure 4.9). The change in height would be $h = 1.5\ \text{m} - 1\ \text{m} = 0.5\ \text{m}$, and the work done by us in moving the book is the same 4.9 J. This tells us that the work done against the force of gravity on the book of mass m depends only on the difference in heights as we lift it from 0.5 to 1 m above the ground; that is, the work depends on the initial and final heights. Motion perpendicular to the direction of the force of gravity contributes nothing to the work done on the book. The work done does not depend on the path through which the book moved between the two points. We could move it following a straight path between the two end points (path 1 in Figure 4.9), or we could move it to the side first, then up, then to the other side so that it ends at the same end point (path 2); we could, in fact, move the book following any trajectory that begins and ends at the same points (as in path 3); the work done will always be the same. A force with the property to produce work that is independent of the path, such as the gravitational force, is called a *conservative force*.

If, on the other hand, you reach for a book that lies on your desk at the other end of where you are and slide it toward you following a straight path (Figure 4.10), the work done against the force of friction that exists between the book and the surface of the desk is less than if you decide to slide the book between the same initial and final points following some other path longer than the previous straight path. In this case, the work done against the force of friction does depend on the path taken. We call these forces, like the force of friction, *nonconservative forces*.

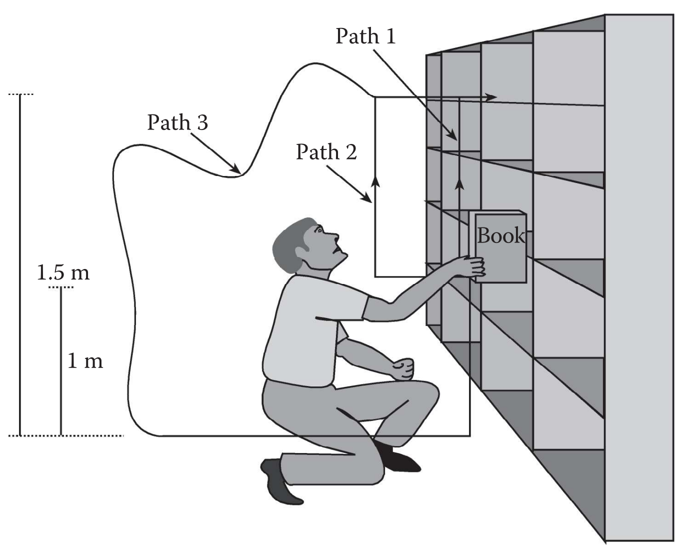

FIGURE 4.9 Three different paths that can be followed to move a book from a shelf 1 m high to a second shelf 1.5 m high. The work done against gravity is the same in all three cases.