All electrons are initially aimed toward the center of the viewing screen, which lights up at a tiny spot wherever electrons hit. To create an image, the electrons must be deflected from the center to a chosen spot on the screen. This is done by deflection plates, which create electric forces and will be explained in a later chapter. Each electron feels the force created by the deflection plates for only a brief time while passing between the deflection plates.

In the example shown, the force, shown as a bold arrow at the deflection plate, acts in the “up” direction, which is perpendicular to the initial “forward” direction of travel. How strong must the deflection force be to make the electron hit the screen 0.1 meters above the center spot? During the 20 nanoseconds of time the electron is traveling from the deflector to the screen, it must travel 0.1 meters in the “up” direction. This means that its up speed must be

$$S = \frac{D}{t} = \frac{0.1\text{m}}{20 \times 10^{-9}\text{ sec}} = 5 \times 10^{6}\text{ m / sec;}$$

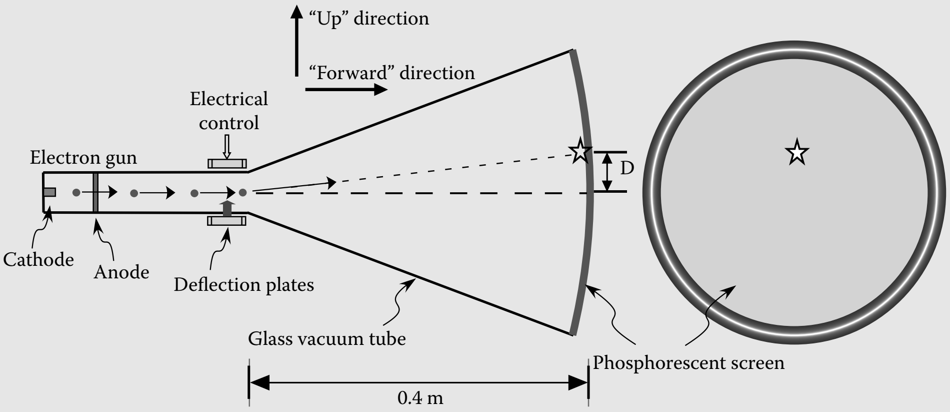

FIGURE 3.13 Electron acceleration in CRT.

that is, 5 million m/sec. The upward acceleration of the electron takes place only during the time interval when the electron is between the two deflection plates. This very short acceleration interval (t') is about 1 nanosecond in duration. The amount of upward acceleration (a) provided by the plates during that time must be truly enormous to achieve such a fast upward speed (S). Recall that $S = a \cdot t$, so:

$$a = \frac{S}{t'} = \frac{5 \times 10^{6}\text{m/sec}}{1 \times 10^{-9}\text{sec}} = 5 \times 10^{15}\text{m/sec}^{2}$$

Compare this to the acceleration provided by gravity near the Earth’s surface, which equals 9.8 m/sec^2. The upward or sideways acceleration experienced by the electrons in the CRT is about 5×10^{14} times higher! The forces used to create such huge accelerations are electrical in nature and are the subject of Chapter 5.

3.3 PRINCIPLES OF MECHANICS

Isaac Newton was the first to realize that the motions of objects obey a particular set of rules. A physical rule that is never observed to be violated is called a law, as we discussed in Chapter 1. Newton was the first to state these laws as quantitative (mathematical) rules that were capable of not only summarizing what was happening in a performed experiment, but also of predicting the outcome of experiments not yet carried out. This was revolutionary in the evolution of science.

Newton recognized three important principles of mechanics, often called Newton's Laws of Motion. The first is:

MECHANICS PRINCIPLE (I)

Newton's first law: An object's speed and direction remain constant unless an external force, which is not balanced by other forces, acts on the object.

This implies, for example, that if there is no friction present, no force is needed to keep an already moving object in motion.

Any change in an object's speed or direction requires a force. Simply maintaining the speed and direction does not require a force. In particular, an *unbalanced* force is required to change the object's speed or direction, because two forces could be applied to an object in a way that their influences balance or cancel each other. For example, if the designer of a jet car mistakenly specified two engines pointing in opposite directions, their forces would balance, leaving zero acceleration.

It is remarkable that Newton, following a tradition begun by Galileo, was able to understand this nonintuitive fact. Newton had no access to human experience in outer space, as we do, but he could observe the motions of planets traveling around the Sun. He realized that any object (we can imagine the astronaut's wrench) would move according to the same rules as the planets moving around the Sun. He recognized that these rules are a consequence of gravity, which is a force of attraction between any two material objects. Although Newton's mathematical formulas could accurately describe and even predict the motion of planets, he was puzzled by the fact that a force can exist between two objects that are so far away from each other; for example, the attractive gravitational force between the Sun and the Earth. Newton was wise enough to realize that he had no deep understanding of the mechanism that is responsible for the gravitational force. Regarding the question of how gravitation was transmitted from object to object across the void (the vacuum of space), he said, "I make no hypotheses."

Newton also recognized that the same amount of force being applied to two different objects could result in different amounts of acceleration if the two objects have different internal properties. For example, a force acting on a tennis ball will lead to a larger acceleration than would the same force acting on a bowling ball. Newton used the word ***mass*** to indicate the reluctance of an object to accelerate when subjected to a force. He formulated his most important principle as follows:

MECHANICS PRINCIPLE (II)

Newton's second law: Acceleration of an object is proportional to the force applied to it, and inversely proportional to the object's mass. In equation form, acceleration equals force divided by mass:

$$\text{acceleration} = \frac{\text{force}}{\text{mass}} \quad \text{or} \quad a = \frac{F}{M}$$

Newton's second law can also be written in a different form if we multiply both sides of the equation by M:

$$\text{force} = \text{mass} \times \text{acceleration}$$
$$F = M \times a$$

Mass refers to the amount of "stuff" that makes up an object. Nowadays we know that this stuff is atoms (made of protons, electrons, and neutrons), but in Newton's day,

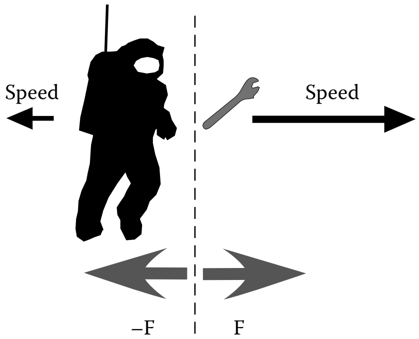

FIGURE 3.14 A free-"floating" astronaut exerts a force equal to *F* on a wrench, causing it to accelerate. The wrench exerts an equal and opposite force on the astronaut, causing her to accelerate in the opposite direction, but to a much smaller speed than the wrench.

scientists simply thought of the amount of "material." In honor of Sir Isaac Newton, we measure the strength of forces in terms of units (amounts) called newtons, abbreviated N. One newton is defined as the amount of force needed to accelerate an object with mass 1 kg at a rate of 1 m/sec^2. Newton's first law is actually a consequence of his second law: if the force is zero, then the acceleration is zero. The reason the first law is stated as a law is for emphasis.

As an example, imagine our astronaut in orbit floating freely and holding a wrench, as in **Figure 3.14**. She places the wrench in her open palm and pushes it away toward space. Say she exerts a force equal to 1 N. During the push, the wrench will experience an acceleration equal to 1 N divided by the mass of the wrench. If the wrench has mass equal to 0.5 kilograms, the acceleration will be:

$$\text{acceleration} = \frac{1\text{ N}}{0.5\text{kg}} = 2\text{m}/\text{sec}^2$$

After the push is finished, the wrench will feel no further acceleration (except perhaps from gravity, but let us ignore that here).

Note that for this example calculation to give the correct answer, we had to express the mass in kilograms (1 kg = 1,000 g), and the acceleration in m/sec^2. We will discuss the matter of units in more detail later in this chapter.

REAL-WORLD EXAMPLE 3.3: FORCE ON A HARD-DRIVE HEAD

In Real-World Example 3.1, we found that the read/write head in a hard disk drive experiences a huge acceleration when moving from point to point above the disk. How much force is needed to achieve such a high acceleration of the head? To answer this, we need to know the head's mass. An estimated value is 1×10^{-5} kg, a small mass. We find the required force using Newton's second law:

$$\begin{aligned} F &= M \cdot a \\ &= 1 \times 10^{-5}\text{ kg} \cdot 1{,}300\text{ m/sec}^2 = 0.013\text{ kg m/sec}^2 = 0.013\ N \end{aligned}$$

We conclude that the force applied to the head during the first 2.5 milliseconds equals 0.013 *N*. The force applied during the second 2.5 milliseconds is the negative of that. This is a rather small force, but when applied to such a small mass, it results in a very high acceleration.

The value 0.013 *N* is the force applied to the head alone. The motor must also accelerate the metal arm that holds the head, and this weighs about 10 times more than the head. This requires an actual applied force about 10 times higher than our estimate for the head alone. This force is exerted in the form of a rotational force, called a *torque*, around the rotation axis of the arm swivel axis.

Mechanics Principle (iii)

Forces always come in pairs. This is described by Newton's third law:

Newton's third law: When one object exerts a force on a second object, the second object also exerts a force, equal in strength and opposite in direction, back on the first object.

For example, if you lean steeply with your hand against a rigid wall, your hand exerts a force on the wall, yet the wall does not accelerate. This is because the wall is strong enough to oppose the applied force of your hand. This means that the wall bends by an imperceptible amount, and in doing so it acts like a stiff spring that exerts a force back on your hand. The fact that neither the wall nor your hand are accelerating proves that the two forces involved are equal in strength and opposite in direction.

Considering again our example in Figure 3.14, this law says that when the astronaut pushes away the wrench with a force of 1 N, she will feel a pushing force back from the wrench, also equal to 1 N. But, because her mass is larger than the wrench, say 100 kilograms including her spacesuit, her acceleration will be much less the wrench's:

$$acceleration = \frac{-1\ \text{N}}{100\ \text{kg}} = -\,0.01\ \text{m/sec}^2$$

Her acceleration is denoted as negative, because she accelerates in the opposite direction than does the wrench.

QUICK QUESTION 3.3

Explain how Newton's third law applies to the acceleration of a jet car, keeping in mind that the purpose of the jet engine is to eject gas out of the back end at high speed.

3.3.1 Gravity's Force

The force of gravity on an object near the Earth's surface equals 9.8 N for every kilogram of mass in the object (i.e., 9.8 N/kg). Consider a skateboarder, with a mass of 34 kilograms, who suddenly drops over the lip of a large ramp. The downward force of gravity on him is

$$34\ \text{kg} \times 9.8\ \text{N/kg} = 333\ \text{N (about 75 lb of force)}$$

One newton equals the force that Earth's gravity (at sea level) exerts on an object with mass equal to 0.102 kilograms. One newton of force is equivalent to 0.225 pounds, or about one-quarter of a pound. That is, to hold up a quarter-pound hamburger, you need to exert a force of 1 N in the upward direction. It is a fun fact—but only a coincidence—that a medium sized apple weighs about a quarter pound. This means that the force of gravity on that proverbial apple that Isaac Newton watched falling from a tree equaled about 1 N, in today's terminology.

We can express gravity's force acting on an object with mass M by the equation:

$$force\ of\ gravity = M \times 9.8\text{N/kg}$$

For example, a bowling ball with a mass of 4 kilograms would experience a force of gravity equal to:

$$force\ of\ gravity = 4\text{kg} \times 9.8\text{N/kg} = 39.2\text{N}$$

Gravity is the special case of the attraction between the Earth and all other objects. The force of gravity on an object near the Earth is proportional to the amount of mass in

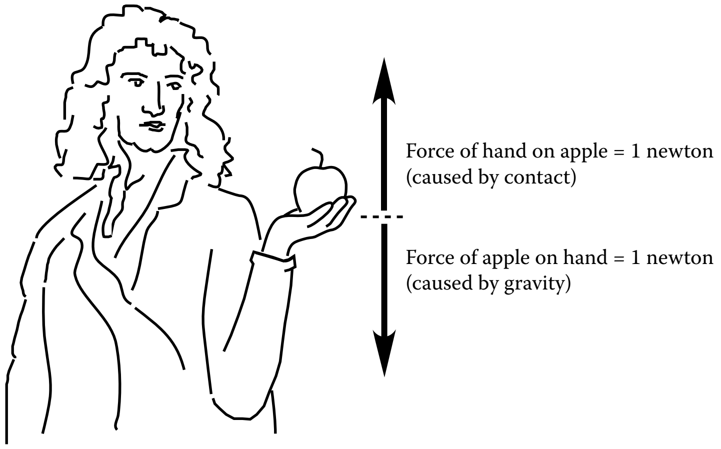

FIGURE 3.15 Newton holding an apple up against gravity.

the object. This leads to the fact, made famous by Galileo, that all objects feel the same acceleration due to Earth's gravity, with a value equal to 9.8 m/sec^2. This can also be stated as 9.8 N per kilogram, or 9.8 N/kg, because 1 N/kg equals 1 m/sec^2. It follows that the force exerted on a mass of 1 kilogram near the Earth's surface is 9.8 N. We can sum up much of our discussion so far using a drawing of Newton simply holding a 0.102-kilogram apple, shown in **Figure 3.15**. Earth's gravity creates a downward force of 1 N on the apple. The apple, by virtue of its contact with the hand, exerts a downward force of 1 N on the hand. Newton, using his muscles, creates an upward force of 1 N, which is exerted on the apple. At the point of contact between the apple and the hand, these two forces are equal in strength and opposite in direction. Therefore, the acceleration is zero.

3.4 THE PHYSICS OF ENERGY

> There is an intuitive feeling that one will not be able to get something for nothing. It therefore seems proper and orderly to suppose that the universe possesses a fixed amount of something or other and that, while this may be distributed among different bodies of the universe in various ways, the total amount may neither be increased nor decreased.
>
> **Isaac Asimov**
> **(***The History of Physics***)**

The concept of ***energy*** gives us a deeper understanding of the motion of objects. If, at the end of a long day, you feel the need for an energy boost, there are two ways you could get one. You could drink a cup of coffee or you could eat a so-called "energy bar." These would have quite different effects, from a physics perspective. The coffee would stimulate your body to a higher level of activity, requiring a more rapid conversion of stored ***chemical energy*** into physical activity for a certain time. After a while, this would decrease the energy stored in your body. In contrast, the energy bar, which is loaded with sugar, would add to the energy content of your body, allowing you to perform more vigorous physical and mental tasks or the same tasks for a longer time. What is energy?

Energy is an intangible quantity in nature that enables one object to cause the motion of another object.

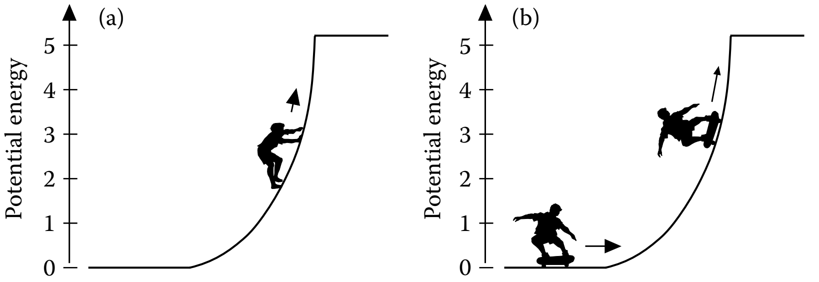

FIGURE 3.16 The top lip of a skateboarding ramp represents higher gravitational potential energy than the bottom of the ramp, which is indicated as zero energy.

Energy comes in distinct forms: kinetic, potential, chemical, and thermal, among others. As an example of ***kinetic energy*** and ***potential energy***, consider a skateboarder at the bottom of a skateboard ramp, as in **Figure 3.16**. If he wants to get to the top of the ramp so he can drop in and begin his ride, he first needs a boost of energy to do so. This energy boost allows him to overcome gravity—the force of the Earth pulling him toward the ground. He could get that boost in several ways–he could use his muscles, converting stored chemical energy (Remember that candy he ate earlier?) into ***mechanical energy***, which allows him to climb up the ramp. Another skater decides to use a different technique to reach the top of the ramp to start her ride. She backs up and accelerates by the familiar foot-on-ground pushing motion. If, before reaching the base of the ramp, she has gained sufficient kinetic energy, then when she reaches the base she will smoothly sail up the ramp, all the while slowing down, and land gracefully on her feet at the top (and catch her board in her hand if she is good). In this example she has first converted stored chemical muscle energy into kinetic energy, then—by rolling up the ramp—has converted that kinetic energy into potential energy. Energy is measured in joules or kilojoules. One kilojoule is the amount of energy required to raise a 34-kilogram skater to a height of 3 meters against gravity (on Earth at sea level).

Once at the top, the skaters have expended some chemical energy from their muscles, and have gained in stored ***gravitational energy***. We say that the gravitational energy is stored as potential energy. It has the potential to be released at any time, causing an object's motion. This stored energy can be released suddenly by the skater dropping in from the edge of the ramp, after which he would quickly gain kinetic energy—defined as the energy associated with motion.

Now our skateboarders are at the top, ready to drop in. Say that this ramp is a half pipe with equal heights at both sides, as in **Figure 3.17**. Our first skater knows that if he

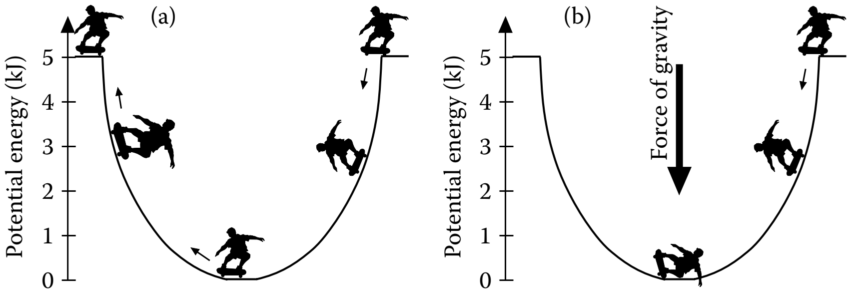

FIGURE 3.17 (a) The skater drops in from the right lip and rolls, without friction, ending up at the lip on the left, with zero speed. (b) The skater falls and, because of friction, ends up at rest at the bottom of the ramp

drops in suddenly and heads straight down the ramp, he will reach a maximum speed at the bottom (lowest point) and, if the ramp is very smooth with no friction (and if he has recently cleaned and oiled his bearings), he will sail exactly up to the lip of the ramp at the other side, where he can simply step onto it and again be at rest. He will not overshoot the lip and sail 20 feet beyond it, and he will not fail to reach the lip entirely.

We are assuming that this skateboard exhibition takes place on Earth, where gravity is present. (Try to imagine skateboarding on a ramp in outer space, where there is little gravity.) This means that there is always a downward force of gravity, pushing a skateboarder toward the center of the Earth. Therefore, when the first skateboarder slowly climbs up the ramp, his muscles are exerting themselves against the force of gravity. He is working against gravity. Physicists call this kind of exertion doing work.

A useful way to think of ***work*** is that it is an action, involving motion, that you would be willing to pay money to someone for performing, such as pushing you up the ramp so you do not have to tire yourself by climbing. Another example would be that you are willing to pay the power utility company to provide you with electricity—the amount you pay each month is proportional to the amount of electrical energy you use to enable your household devices to perform work for you. Washing machines wash; light bulbs light; CD players play. A final example would be that you are willing to pay for a lift ticket at a ski resort because, after the lift has done enough work to enable you to reach the top, you have acquired sufficient potential energy that you can then ski down the hill and have all kinds of fun. (Fun is not a technical physics term, although maybe it should be.) When we say that work is an action that you would be willing to pay for, we mean by the word *action* that there is a force acting on a moving object through a distance. Therefore, if a person stands still and holds your heavy suitcase off the ground for 1 minute, he or she might be expending chemical muscle energy, but that does not mean the person is doing work in the technical sense.

Work is defined as follows:

Work is the process of applying a force over a certain distance.

More precisely, work is the amount of energy transferred when moving an object through a certain distance by applying a force in the direction of motion. When you do work on an object, you transfer energy from yourself to it. In terms of an equation, work equals the strength of the applied force multiplied by the distance the object moves.

$$\text{Work} = \text{Force} \times \text{Distance Moved}$$
$$W = F \times D$$

Using this concept of work, we can turn the definition of energy around and say:

Energy is the capacity of a physical system to do work.

Force doing work is illustrated in **Figure 3.18**. The astronaut braces her back against the space shuttle and exerts a steady force, say 1 N, on a ball over a certain distance, say 0.5 meters. In Figure 3.18a, the ball is a heavy bowling ball, so after the force is exerted, and the work is done, this ball ends up moving at a fairly slow speed. In Figure 3.18b, the ball is a light ping-pong ball, which is easier to accelerate. So, after the force is exerted over the same distance, and the same work is done, this ball ends up moving at a higher speed. In both cases, the amount of work done is the same (*force* × *distanc*e). Therefore

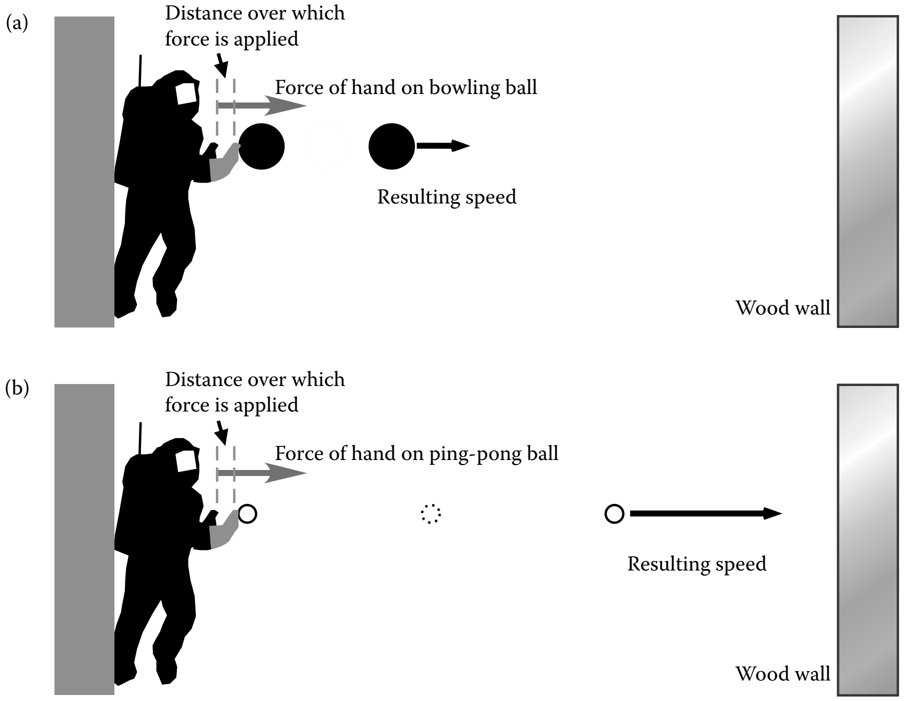

FIGURE 3.18 By applying the same force over the same distance, an astronaut does equal amounts of work on a bowling ball and on a ping-pong ball.

the amount of kinetic energy given to the balls is the same.[2] That is, the amount of work done on an object does not depend on the size of the object's mass—only on the force and the distance through which it is pushed.

Let us try to understand this counterintuitive conclusion in the case of the two balls. We can get a feeling for how much kinetic energy a moving object possesses by thinking about how much damage the object could do if it were to run head-on into a fixed wall made of a material such as wood covered with a thick, soft fabric so that the object does not bounce from the surface. Both balls could break the wooden wall. It should seem reasonable to you that the fast-moving ping-pong ball could do as much damage to this wall as could the slow-moving bowling ball. This is true, because they have the same amount of kinetic energy before they hit the wall.

A second example shows how the potential energy of an object is increased by doing work on it. In **Figure 3.19a**, a wheeled cart is slowly pulled up a ramp against the force of gravity by a steady, applied force equal to 5 N. The cart gains a height of 1 meter. The length of the ramp is 3 meters, so the work done on the cart equals

$$Work = 5\text{ N} \times 3\text{ m} = 15\text{ J}$$

Therefore, the potential energy gained by the cart is 15 joules. In Figure 3.19b, the same cart is pulled straight up, gaining the same height, 1 meter. The steady force required to pull the cart straight up against gravity equals 15 N, larger than in the case of pulling it up the ramp.

$$Work = 5\text{ N} \times 1\text{ m} = 15\text{ J}$$

In both cases, the potential energy given to the cart depends only on the height to which it is raised, in both cases 1 meter. That is, after being raised to this height,

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[2] The formula for the amount of kinetic energy possessed by an object having mass M, moving with speed S is: $(1/2)MS^2$, but we will not use this formula.

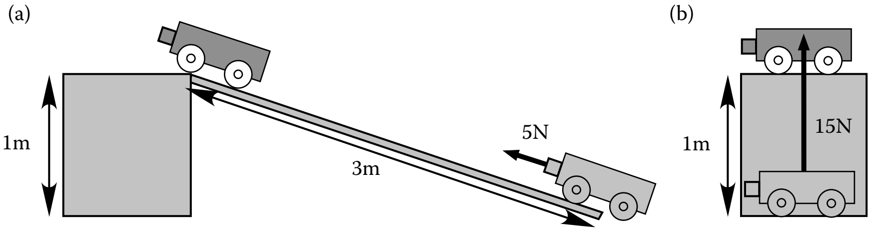

FIGURE 3.19 The amount of work that needs to be done to raise a cart by a height of 1 m is the same if we pull it up an incline or raise it straight up.

the cart has the potential to do a fixed amount of work (or damage) on some other object.

To summarize, changes of energy (increases or decreases) involve either having work done on an object or work done by that object. Forces are needed for this to occur.

3.5 FRICTION AND THERMAL ENERGY

If, as in Figure 3.17b, the skateboarder falls off her board just after dropping in, then the *friction* between her clothes or skin and the ramp surface will cause her to slow down, and she will not sail up to the edge of the ramp lip at the far side of the half pipe. What happened to her stored potential energy, which had been converted to kinetic energy as she dropped in? The answer is that her clothes and skin (and the ramp) heated up. All of the stored potential energy was converted into ***thermal energy*** (see the next section). ***Friction*** is the process by which kinetic energy is converted into thermal energy when two surfaces rub together.

What causes friction? If you push two surfaces together and try to slide them past each other, there will be some resisting force, which is friction. To understand it, first realize that no surface is perfectly smooth. Some roughness will always be seen under a powerful enough microscope, as illustrated in **Figure 3.20**. Think of two pieces of sand paper being rubbed together. Friction between them is caused by the tiny protrusions on the two surfaces bumping into each other and possibly sticking together temporarily. Friction causes a force between two objects when their surfaces are in contact and they are moving relative to each other. The friction force always opposes the motion of one object relative to the other. Typically, the force provided by friction increases for the higher speed of one surface relative to the other. When an object falls through the atmosphere, air resistance causes a type of friction on the object.

Thermal energy is the microscopic kinetic and potential energies associated with the random motions of the particles, called atoms, making up a solid, liquid, or gas. Thermal energy is also called internal energy. The warmer a substance is, the faster its internal atoms move on average. ***Temperature*** is the term we use to designate the

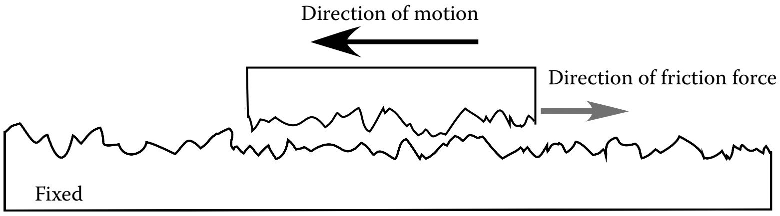

FIGURE 3.20 Two surfaces sliding while in contact, viewed under high magnification. The friction force is in the opposite direction from the motion.