5-4

Work, energy, and power

5-4 SECTION OBJECTIVES

- **Apply the work–kinetic energy theorem to solve problems.**
- **Relate the concepts of energy, time, and power.**
- **Calculate power in two different ways.**
- **Explain the effect of machines on work and power.**

THE WORK–KINETIC ENERGY THEOREM

Imagine that a person kicks a sled initially at rest on a frozen pond, as shown in **Figure 5-12.** There is kinetic friction between the sled and the ice, so the sled slows down and eventually stops. How far does the sled move?

Clearly, mechanical energy is not conserved, but there is a relationship between the work done on the sled and the change in the kinetic energy of the sled. This relationship is known as the **work–kinetic energy theorem** and is written as follows:

work–kinetic energy theorem

the net work done on an object is equal to the change in the kinetic energy of the object

WORK–KINETIC ENERGY THEOREM

$$W_{net} = \Delta KE$$

net work = change in kinetic energy

Notice that the type of force acting on the object is not specified in the work–kinetic energy theorem. Because it could be any force, the theorem applies to all objects universally. There is an alternative form for the work–kinetic energy theorem that is useful when the work is done by friction:

$$W_{friction} = \Delta ME$$

If a problem does not involve friction, then $W_{friction} = 0$ and the above equation can be simplified.

$$\Delta ME = 0$$

$$ME_i = ME_f$$

This is a statement of conservation of mechanical energy. Notice that the work–kinetic energy theorem in either form demonstrates that work is a method of transferring energy. A force that is perpendicular to the displacement of an object does no work on the object because no energy is transferred.

In solving problems, it is important to make a distinction between the two expressions $W = Fd(\cos\theta)$ and $W_{net} = \Delta KE$. The first expression applies to the work done by one object on another and is the definition of work. The second expression applies only to the net force on an object and relates the net work done on an object to the change in kinetic energy.

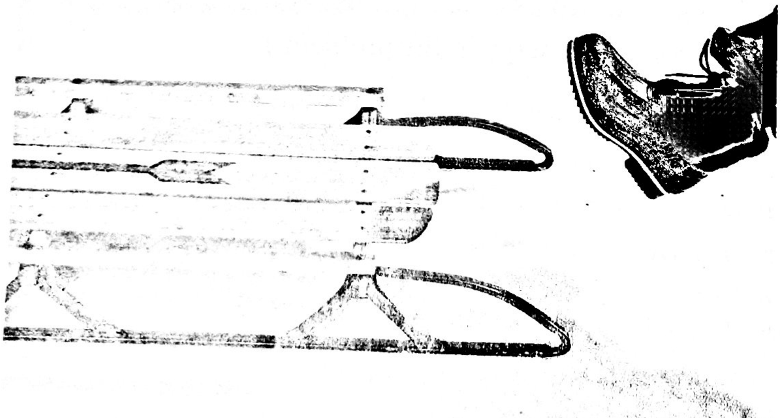


Figure 5-12

The net energy transferred to the sled by work equals the change in the sled's kinetic energy.

Work–kinetic energy theorem

PROBLEM

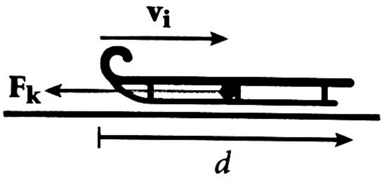
On a frozen pond, a person kicks a 10.0 kg sled, giving it an initial speed of 2.2 m/s. How far does the sled move if the coefficient of kinetic friction between the sled and the ice is 0.10?

SOLUTION

1. DEFINE **Given:** $m = 10.0$ kg $v_i = 2.2$ m/s $v_f = 0$ m/s $\mu_k = 0.10$

Unknown: $d = ?$

Diagram:



2. PLAN **Choose an equation(s) or situation:** This problem can be solved using the definition of work and the work–kinetic energy theorem.

$$W_{net} = F_{net}d(\cos\theta)$$
$$W_{net} = \Delta KE$$

The initial kinetic energy is given to the sled by the person.

$$KE_i = \frac{1}{2}mv_i^2$$

Because the sled comes to rest, the final kinetic energy is zero.

$$KE_f = 0$$
$$\Delta KE = KE_f - KE_i = -\frac{1}{2}mv_i^2$$

The net work done on the sled is provided by the force of kinetic friction.

$$W_{net} = F_{net}d(\cos\theta) = \mu_k mgd(\cos\theta)$$

The force of kinetic friction is in the direction opposite d.

$$\theta = 180°$$

3. CALCULATE **Substitute values into the equations:**

$$W_{net} = (0.10)(10.0\text{ kg})(9.81\text{ m/s}^2)\,d\,(\cos 180°)$$
$$= (-9.8\text{ N})d$$
$$\Delta KE = -KE_i = -(0.50)(10.0\text{ kg})(2.2\text{ m/s})^2 = -24\text{ J}$$

Use the work–kinetic energy theorem to solve for d.

$$W_{net} = \Delta KE$$
$$(-9.8\text{ N})d = -24\text{ J}$$

$$\boxed{d = 2.4\text{ m}}$$

CALCULATOR SOLUTION

Your calculator should give an answer of 2.44898, but because the answer is limited to two significant figures, this should be rounded to 2.4.

continued on next page

4. EVALUATE Note that because the direction of the force of kinetic friction is opposite the displacement, the net work done is negative. Also, according to Newton's second law, the acceleration of the sled is about $-1\ \text{m/s}^2$ and the time it takes the sled to stop is about 2 s. Thus, the distance the sled traveled in the given amount of time should be less than the distance it would have traveled in the absence of friction.

$$2.4\ \text{m} < (2.2\ \text{m/s})(2\ \text{s}) = 4.4\ \text{m}$$

PRACTICE 5E

Work–kinetic energy theorem

1. A 2.0×10^3 kg car moves down a level highway under the actions of two forces. One is a 1140 N forward force exerted on the wheels by the road. The other is a 950 N resistive force exerted on the car by the air. Use the work–kinetic energy theorem to find the speed of the car after it has moved a distance of 20.0 m, assuming the car starts from rest.

2. A 2.10×10^3 kg car starts from rest at the top of a driveway 5.0 m long that is sloped at 20.0° with the horizontal. If an average friction force of 4.0×10^3 N impedes the motion, what is the speed of the car at the bottom of the driveway?

3. A 10.0 kg crate is pulled up a rough incline with an initial speed of 1.5 m/s. The pulling force is 100.0 N parallel to the incline, which makes an angle of 15.0° with the horizontal. Assuming the coefficient of kinetic friction is 0.40 and the crate is pulled a distance of 7.5 m, find the following:

- **a.** the work done by the Earth's gravity on the crate
- **b.** the work done by the force of friction on the crate
- **c.** the work done by the puller on the crate
- **d.** the change in kinetic energy of the crate
- **e.** the speed of the crate after it is pulled 7.5 m

POWER

power

the rate at which energy is transferred

The rate at which work is done is called **power.** More generally, power is the rate of energy transfer by any method. Like the concepts of energy and work, power has a specific meaning in science that differs from its everyday meaning

Imagine you are producing a play and you need to raise and lower the curtain between scenes in a specific amount of time. You decide to use a moto that will pull on a rope connected to the top of the curtain rod. Your assistan finds three motors but doesn't know which one to use. One way to decide is to consider the power output of each motor.

If the work done on an object is W in a time interval Δt, then the power delivered to the object over this time interval is written as follows:

Did you know?

Your heart uses an average of about 1.1 W to pump blood through your body.

POWER

$$P = \frac{W}{\Delta t}$$

power = work ÷ time

It is sometimes useful to rewrite this equation in an alternative form by substituting the definition of work into the definition of power.

$$W = Fd$$

$$P = \frac{W}{\Delta t} = F\frac{d}{\Delta t}$$

The distance moved per unit time is just the speed of the object.

POWER (ALTERNATIVE FORM)

$$P = Fv$$

power = force × speed

The SI unit of power is the *watt*, W, which is defined to be 1 J/s. The *horsepower*, hp, is another unit of power that is sometimes used. One horsepower is equal to 746 W.

The watt is perhaps most familiar to you from your everyday experience with light bulbs (see **Figure 5-13**). A dim light bulb requires about 40 W to operate, while a bright bulb can require up to 500 W. Decorative lights need about 0.7 W each for indoor lights and 7.0 W each for outdoor lights.

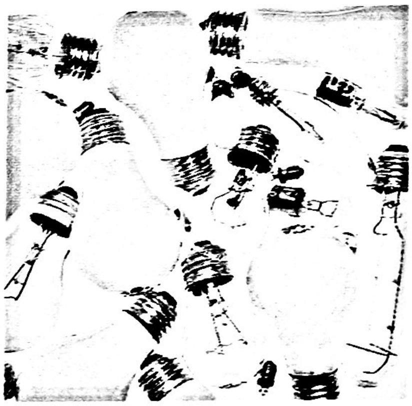
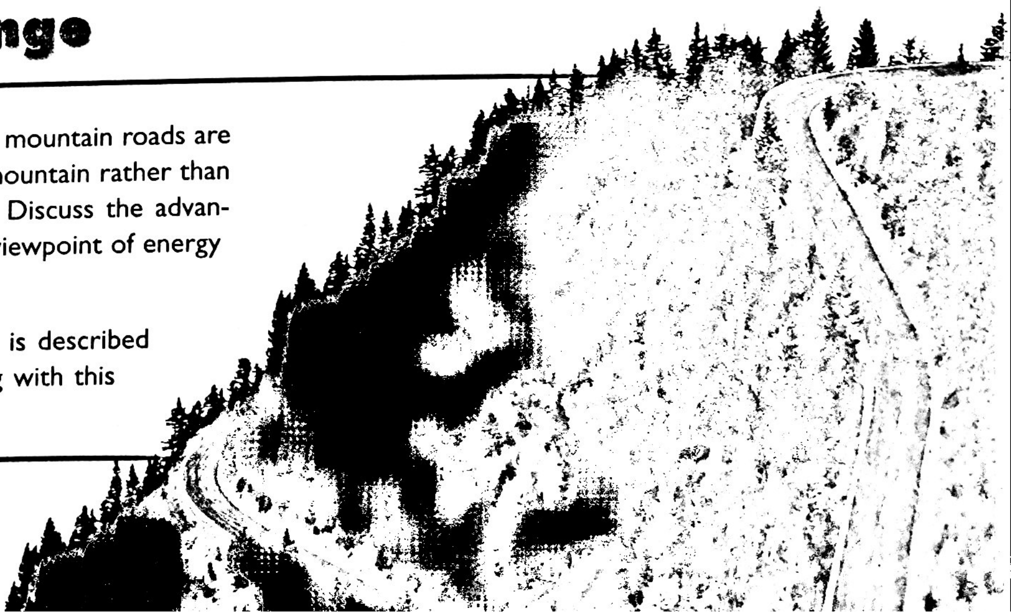


Figure 5-13
The wattage of each of these bulbs tells you the rate at which energy is converted by the bulb. The bulbs in this photo require wattages ranging from 0.7 W to 200 W.

Conceptual Challenge

1. Mountain roads Many mountain roads are built so that they zigzag up the mountain rather than go straight up toward the peak. Discuss the advantages of such a design from the viewpoint of energy conservation and power.

2. Light bulbs A light bulb is described as *having* 60 watts. What's wrong with this phrase?



SAMPLE PROBLEM 5F

Power

PROBLEM

A 193 kg curtain needs to be raised 7.5 m in as close to 5.0 s as possible. Three motors are available. The power ratings for the three motors are listed as 1.0 kW, 3.5 kW, and 5.5 kW. Which motor is best for the job?

SOLUTION

Given: $m = 193\ \text{kg} \quad \Delta t = 5.0\ \text{s} \quad d = 7.5\ \text{m}$

Unknown: $P = ?$

Use the power equation from page 187.

$$P = \frac{W}{\Delta t} = \frac{Fd}{\Delta t} = \frac{mgd}{\Delta t}$$

$$= \frac{(193\ \text{kg})(9.81\ \text{m/s}^2)(7.5\ \text{m})}{5.0\ \text{s}}$$

$$P = 2.8 \times 10^3\ \text{W} = 2.8\ \text{kW}$$

The best motor to use is the 3.5 kW motor. The 1.0 kW motor will not lift the curtain fast enough, and the 5.5 kW motor will lift the curtain too fast.

Machines with different power ratings do the same work in different time intervals

In Sample Problem 5F, the three motors would lift the curtain at different rates because the power output for each motor is different. This means that each motor would do work on the curtain at different rates, thus transferring energy to the curtain at different rates.

In a given amount of time, each motor would do different amounts of work on the curtain. The 5.5 kW motor would do the most amount of work in a given time, and the 1.0 kW motor would do the least amount of work in the same time. Yet they would all perform the same total amount of work in lifting the curtain. The important difference is that the more powerful motor could do the work in a shorter time interval.

CONCEPT PREVIEW

Machines will be discussed further in Chapter 8.

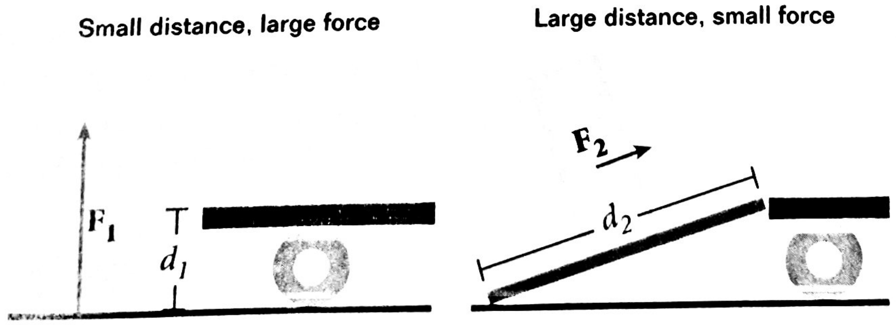
Section Review

1. A 50.0 kg parachutist jumps out of an airplane at a height of 1.00 km. The parachute opens, and the jumper lands on the ground with a speed of 5.00 m/s. By what amount was the jumper's mechanical energy reduced due to air resistance during this jump? What was the average force of air friction during the jumper's descent if the parachute opened immediately after jumping?

2. A 50.0 kg student climbs 5.00 m up a rope at a constant speed. If the student's power output is 200.0 W, how long does it take the student to climb the rope? How much work does the student do?

3. How are energy, time, and power related?

4. Two movers have to lift a refrigerator onto a truck, as shown in **Figure 5-14.** One of the movers wants to lift the refrigerator vertically, but the other mover wants to roll it up a ramp by applying a force parallel to the ramp. Assume the height of the truck is 1.5 m, the length of the ramp is 5.0 m, and the weight of the refrigerator is 1200.0 N. Calculate the force and the total work required in each case. Which method is easier?


Small distance, large force

Large distance, small force

Figure 5-14