Chapter 10 Energy, Work, and Simple Machines

What You'll Learn

- You will recognize that work and power describe how the external world changes the energy of a system.
- You will relate force to work and explain how machines ease the load.

Why It's Important

Simple machines and the compound machines formed from them make many everyday tasks easier to perform.

Mountain Bikes A multispeed mountain bicycle with shock absorbers allows you to match the ability of your body to exert forces, to do work, and to deliver power climbing steep hills, traversing flat terrain at high speeds, and safely descending hills.

Think About This ▶

How does a multispeed mountain bicycle enable a cyclist to ride over any kind of terrain with the least effort?

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LAUNCH Lab

What factors affect energy?

Question
What factors affect the energy of falling objects and their ability to do work?

Procedure

1. Place about 2 cm of fine sand in the bottom of a pie plate or baking pan.
2. Obtain a variety of metal balls or glass marbles of different sizes.
3. Hold a meterstick vertically in one hand, with one end just touching the surface of the sand. With the other hand, drop one of the balls into the sand. Record the height from which you dropped the ball.
4. Carefully remove the ball from the sand, so as not to disturb the impact crater it made. Measure the depth of the crater and how far sand was thrown from the crater.
5. Record the mass of the ball.
6. Smooth out the sand in the pie plate and perform steps 3–5 with different sizes of balls and drop them from varying heights. Be sure to drop different sizes of balls from the same height, as well as the same ball from different heights.

Analysis

Compare your data for the different craters. Is there an overall trend to your data? Explain.

Critical Thinking As the balls are dropped into the sand, they do work on the sand. Energy can be defined as the ability of an object to do work on itself or its surroundings. Relate the trend(s) you found in this lab to the energy of the balls. How can the energy of a ball be increased?

10.1 Energy and Work

Objectives

- **Describe** the relationship between work and energy.
- **Calculate** work.
- **Calculate** the power used.

Vocabulary

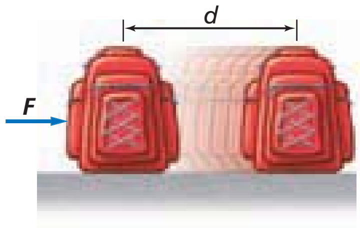
work
energy
kinetic energy
work-energy theorem
joule
power
watt

In Chapter 9, you learned about the conservation of momentum. You learned that you could examine the state of a system before and after an impulse acted on it without knowing the details about the impulse. The law of conservation of momentum was especially useful when considering collisions, during which forces sometimes changed dramatically. Recall the discussion in Chapter 9 of the two skaters who push each other away. While momentum is conserved in this situation, the skaters continue to move after pushing each other away; whereas before the collision, they were at rest. When two cars crash into each other, momentum is conserved. Unlike the skaters, however, the cars, which were moving prior to the collision, became stationary after the crash. The collision probably resulted in a lot of twisted metal and broken glass. In these types of situations, some other quantity must have been changed as a result of the force acting on each system.

Horizons Companies

Work and Energy

Recall that change in momentum is the result of an impulse, which is the product of the average force exerted on an object and the time of the interaction. Consider a force exerted on an object while the object moves a certain distance. Because there is a net force, the object will be accelerated, $a = F/m$, and its velocity will increase. Examine Table 3-3 in Chapter 3, on page 68, which lists equations describing the relationships among position, velocity, and time for motion under constant acceleration. Consider the equation involving acceleration, velocity, and distance: $2ad = v_f^2 - v_i^2$. If you use Newton's second law to replace a with F/m and multiply both sides by $m/2$, you obtain $Fd = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$.



■ **Figure 10-1** Work is done when a constant force, *F*, is exerted on the backpack in the direction of motion and the backpack moves a distance, *d*.

Work The left side of the equation describes something that was done to the system by the external world (the environment). A force, F, was exerted on an object while the object moved a distance, d, as shown in **Figure 10-1**. If F is a constant force, exerted in the direction in which the object is moving, then **work,** W, is the product of the force and the object's displacement.

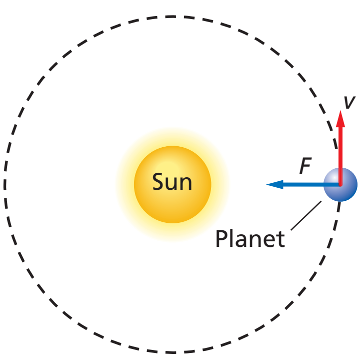
Work $W = Fd$

Work is equal to a constant force exerted on an object in the direction of motion, times the object's displacement.

You probably have used the word *work* in many other ways. For example, a computer might work well, learning physics can be hard work, and you might work at an after-school job. To physicists, however, work has a very precise meaning.

Recall that $Fd = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$. Rewriting the equation $W = Fd$ results in $W = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$. The right side of the equation involves the object's mass and its velocities after and before the force was exerted. The quantity $\frac{1}{2}mv_i^2$ describes a property of the system.

Kinetic energy What property of a system does $\frac{1}{2}mv_i^2$ describe? A massive, fast-moving vehicle can do damage to objects around it, and a baseball hit at high speed can rise high into the air. That is, an object with this property can produce a change in itself or the world around it. This property, the ability of an object to produce a change in itself or the world around it, is called **energy.** The fast-moving vehicle and the baseball possess energy that is associated with their motion. This energy resulting from motion is called **kinetic energy** and is represented by the symbol KE.



■ **Figure 10-2** If a planet is in a circular orbit, then the force is perpendicular to the direction of motion. Consequently, the gravitational force does no work on the planet.

Kinetic Energy $KE = \frac{1}{2}mv^2$

The kinetic energy of an object is equal to $\frac{1}{2}$ times the mass of the object multiplied by the speed of the object squared.

Substituting KE into the equation $W = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$ results in $W = KE_f - KE_i$. The right side is the difference, or change, in kinetic energy. The **work-energy theorem** states that when work is done on an object, the result is a change in kinetic energy. The work-energy theorem can be represented by the following equation.

Work-Energy Theorem $W = \Delta KE$

Work is equal to the change in kinetic energy.

The relationship between work done and the change in energy that results was established by nineteenth-century physicist James Prescott Joule. To honor his work, a unit of energy is called a **joule** (J). For example, if a 2-kg object moves at 1 m/s, it has a kinetic energy of 1 $kg{\cdot}m^2/s^2$, or 1 J.

Recall that a system is the object of interest and the external world is everything else. For example, one system might be a box in a warehouse and the external world might consist of yourself, Earth's mass, and anything else external to the box. Through the process of doing work, energy can move between the external world and the system.

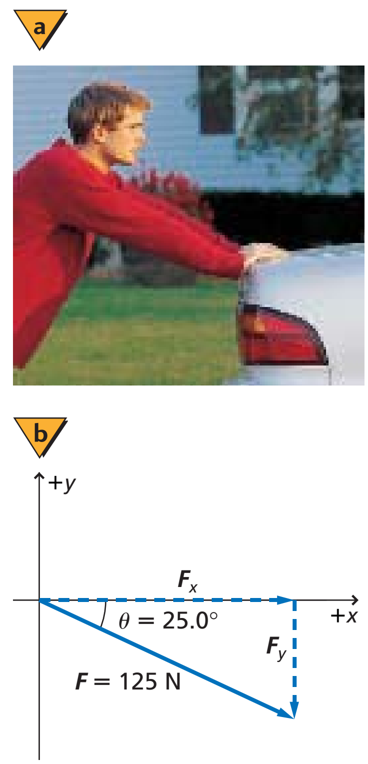
Notice that the direction of energy transfer can go both ways. If the external world does work on a system, then W is positive and the energy of the system increases. If, however, a system does work on the external world, then W is negative and the energy of the system decreases. In summary, work is the transfer of energy by mechanical means.

Calculating Work

The first equation used to calculate work is $W = Fd$. This equation, however, holds only for constant forces exerted in the direction of motion. What happens if the force is exerted perpendicular to the direction of motion? An everyday example of this is the motion of a planet around the Sun, as shown in **Figure 10-2**. If the orbit is circular, then the force is always perpendicular to the direction of motion. Recall from Chapter 6 that a perpendicular force does not change the speed of an object, only its direction. Consequently, the speed of the planet doesn't change. Therefore, its kinetic energy also is constant. Using the equation $W = \Delta KE$, you can see that when KE is constant, $\Delta KE = 0$ and thus, $W = 0$. This means that if F and d are at right angles, then $W = 0$.

Because the work done on an object equals the change in energy, work also is measured in joules. One joule of work is done when a force of 1 N acts on an object over a displacement of 1 m. An apple weighs about 1 N. Thus, when you lift an apple a distance of 1 m, you do 1 J of work on it.

Constant force exerted at an angle You've learned that a force exerted in the direction of motion does an amount of work given by $W = Fd$. A force exerted perpendicular to the motion does no work. What work does a force exerted at an angle do? For example, what work does the person pushing the car in **Figure 10-3a** do? You know that any force can be replaced by its components. If the coordinate system shown in **Figure 10-3b** is used, the 125-N force, $\boldsymbol{F}$, exerted in the direction of the person's arm, has two components. The magnitude of the horizontal component, F_x, is related to the magnitude of the force, F, by a cosine function: $\cos 25.0° = F_x/F$. By solving for F_x, you obtain $F_x = F \cos 25.0° = (125\ \text{N})(\cos 25.0°) = 113$ N. Using the same method, the vertical component $F_y = -F \sin 25.0° = -(125\ \text{N})(\sin 25.0°) = -52.8$ N, where the negative sign shows that the force is downward. Because the displacement is in the x direction, only the x-component does work. The y-component does no work.



■ **Figure 10-3** If a force is applied to a car at an angle, the net force doing the work is the component that acts in the direction of the displacement.

Concepts In Motion
Interactive Figure To see an animation on work by a force acting at an angle, visit physicspp.com.

The work you do when you exert a force on an object, at an angle to the direction of motion, is equal to the component of the force in the direction of the displacement, multiplied by the distance moved. The magnitude of the component force acting in the direction of displacement is found by multiplying the magnitude of force, F, by the cosine of the angle between F and the direction of the displacement: $F_x = F \cos \theta$. Thus, the work done is represented by the following equation.

Work (Angle Between Force and Displacement) $W = Fd \cos \theta$

Work is equal to the product of force and displacement, times the cosine of the angle between the force and the direction of the displacement.

Other agents exert forces on the pushed car as well. Which of these agents do work? Earth's gravity acts downward, the ground exerts a normal force upward, and friction exerts a horizontal force opposite the direction of motion. The upward and downward forces are perpendicular to the direction of motion and do no work. For these forces, $\theta = 90°$, which makes $\cos \theta = 0$, and thus, $W = 0$.

The work done by friction acts in the direction opposite that of motion—at an angle of 180°. Because $\cos 180° = -1$, the work done by friction is negative. Negative work done by a force exerted by something in the external world reduces the kinetic energy of the system. If the person in Figure 10-3a were to stop pushing, the car would quickly stop moving—its energy of motion would be reduced. Positive work done by a force increases the energy, while negative work decreases it. Use the problem-solving strategies below when you solve problems related to work.

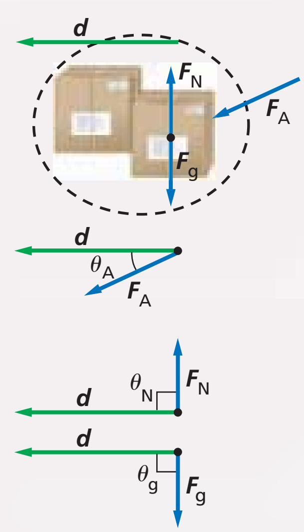
PROBLEM-SOLVING Strategies

Work

When solving work-related problems, use the following strategies.

1. Sketch the system and show the force that is doing the work.
2. Draw the force and displacement vectors of the system.
3. Find the angle, θ, between each force and displacement.
4. Calculate the work done by each force using $W = Fd \cos \theta$.
5. Calculate the net work done. Check the sign of the work using the direction of energy transfer. If the energy of the system has increased, the work done by that force is positive. If the energy has decreased, then the work done by that force is negative.

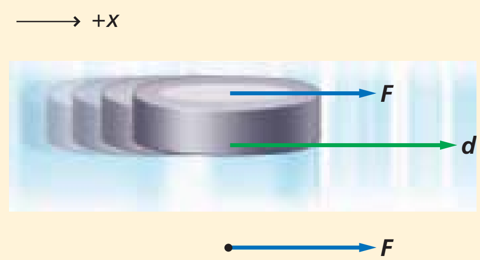
Work Diagram



▶ EXAMPLE Problem 1

Work and Energy A 105-g hockey puck is sliding across the ice. A player exerts a constant 4.50-N force over a distance of 0.150 m. How much work does the player do on the puck? What is the change in the puck's energy?

1 Analyze and Sketch the Problem



- Sketch the situation showing initial conditions.
- Establish a coordinate system with $+x$ to the right.
- Draw a vector diagram.

Known:	**Unknown:**
$m = 105$ g	$W = ?$
$F = 4.50$ N	$\Delta KE = ?$
$d = 0.150$ m	

2 Solve for the Unknown

Use the equation for work when a constant force is exerted in the same direction as the object's displacement.

$$W = Fd$$

$$= (4.50 \text{ N})(0.150 \text{ m})$$ **Substitute $F = 4.50$ N, $d = 0.150$ m**

$$= 0.675 \text{ N·m}$$

$$= 0.675 \text{ J}$$ **1 J = 1 N·m**

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Operations with Significant Digits
pages 835–836

Use the work-energy theorem to determine the change in energy of the system.

$$W = \Delta KE$$

$$\Delta KE = 0.675 \text{ J}$$ **Substitute $W = 0.675$ J**

3 Evaluate the Answer

- **Are the units correct?** Work is measured in joules.
- **Does the sign make sense?** The player (external world) does work on the puck (the system). So the sign of work should be positive.

▶ PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

1. Refer to Example Problem 1 to solve the following problem.

a. If the hockey player exerted twice as much force, 9.00 N, on the puck, how would the puck's change in kinetic energy be affected?

b. If the player exerted a 9.00-N force, but the stick was in contact with the puck for only half the distance, 0.075 m, what would be the change in kinetic energy?

2. Together, two students exert a force of 825 N in pushing a car a distance of 35 m.

a. How much work do the students do on the car?

b. If the force was doubled, how much work would they do pushing the car the same distance?

3. A rock climber wears a 7.5-kg backpack while scaling a cliff. After 30.0 min, the climber is 8.2 m above the starting point.

a. How much work does the climber do on the backpack?

b. If the climber weighs 645 N, how much work does she do lifting herself and the backpack?

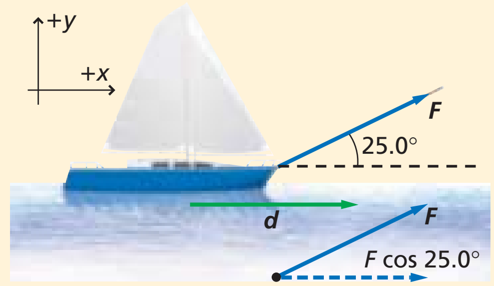
c. What is the change in the climber's energy?

EXAMPLE Problem 2

Force and Displacement at an Angle A sailor pulls a boat a distance of 30.0 m along a dock using a rope that makes a 25.0° angle with the horizontal. How much work does the sailor do on the boat if he exerts a force of 255 N on the rope?

1 Analyze and Sketch the Problem

- Establish coordinate axes.
- Sketch the situation showing the boat with initial conditions.
- Draw a vector diagram showing the force and its component in the direction of the displacement.



Known:	**Unknown:**
$F = 255$ N	$W = ?$
$d = 30.0$ m	
$\theta = 25.0°$	

2 Solve for the Unknown

Use the equation for work done when there is an angle between the force and displacement.

$$W = Fd\cos\theta$$
$$= (255 \text{ N})(30.0 \text{ m})(\cos 25.0°) \quad \text{Substitute } F = 255 \text{ N}, d = 30.0 \text{ m}, \theta = 25.0°$$
$$= 6.93\times10^{3} \text{ J}$$

3 Evaluate the Answer

- **Are the units correct?** Work is measured in joules.
- **Does the sign make sense?** The sailor does work on the boat, which agrees with a positive sign for work.

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PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

4. If the sailor in Example Problem 2 pulled with the same force, and along the same distance, but at an angle of 50.0°, how much work would he do?

5. Two people lift a heavy box a distance of 15 m. They use ropes, each of which makes an angle of 15° with the vertical. Each person exerts a force of 225 N. How much work do they do?

6. An airplane passenger carries a 215-N suitcase up the stairs, a displacement of 4.20 m vertically, and 4.60 m horizontally.

- **a.** How much work does the passenger do?
- **b.** The same passenger carries the same suitcase back down the same set of stairs. How much work does the passenger do now?

7. A rope is used to pull a metal box a distance of 15.0 m across the floor. The rope is held at an angle of 46.0° with the floor, and a force of 628 N is applied to the rope. How much work does the force on the rope do?

8. A bicycle rider pushes a bicycle that has a mass of 13 kg up a steep hill. The incline is 25° and the road is 275 m long, as shown in **Figure 10-4.** The rider pushes the bike parallel to the road with a force of 25 N.

- **a.** How much work does the rider do on the bike?
- **b.** How much work is done by the force of gravity on the bike?

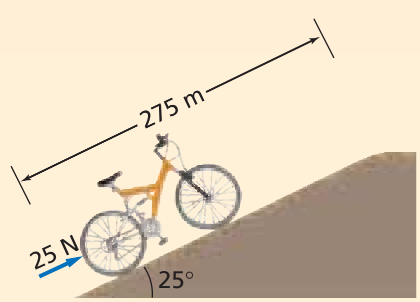
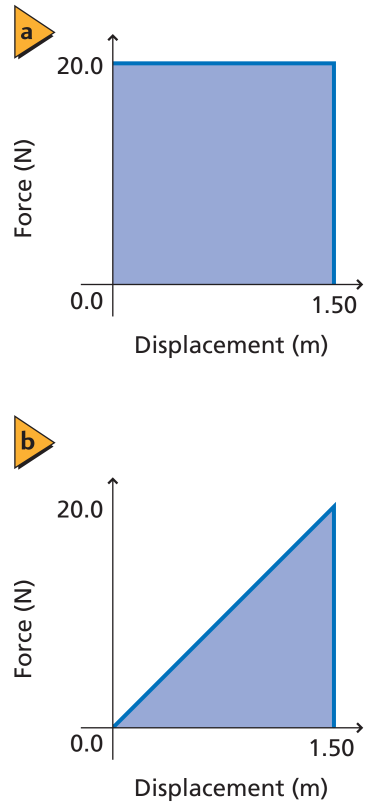


Figure 10-4 (Not to scale)

Finding work done when forces change A graph of force versus displacement lets you determine the work done by a force. This graphical method can be used to solve problems in which the force is changing. **Figure 10-5a** shows the work done by a constant force of 20.0 N that is exerted to lift an object a distance of 1.50 m. The work done by this constant force is represented by $W = Fd = (20.0\ \text{N})(1.50\ \text{m}) = 30.0\ \text{J}$. The shaded area under the graph is equal to (20.0 N)(1.50 m), or 30.0 J. The area under a force-displacement graph is equal to the work done by that force, even if the force changes. **Figure 10-5b** shows the force exerted by a spring, which varies linearly from 0.0 to 20.0 N as it is compressed 1.50 m. The work done by the force that compressed the spring is the area under the graph, which is the area of a triangle, $\frac{1}{2}$(base)(altitude), or $W = \frac{1}{2}(20.0\ \text{N})(1.50\ \text{m}) = 15.0\ \text{J}$.

Work done by many forces Newton's second law of motion relates the net force on an object to its acceleration. In the same way, the work-energy theorem relates the net work done on a system to its energy change. If several forces are exerted on a system, calculate the work done by each force, and then add the results.

■ **Figure 10-5** Work can be obtained graphically by finding the area under a force-displacement graph.



Power

Until now, none of the discussions of work has mentioned the time it takes to move an object. The work done by a person lifting a box of books is the same whether the box is lifted onto a shelf in 2 s or each book is lifted separately so that it takes 20 min to put them all on the shelf. Although the work done is the same, the rate at which it is done is different. **Power** is the work done, divided by the time taken to do the work. In other words, power is the rate at which the external force changes the energy of the system. It is represented by the following equation.

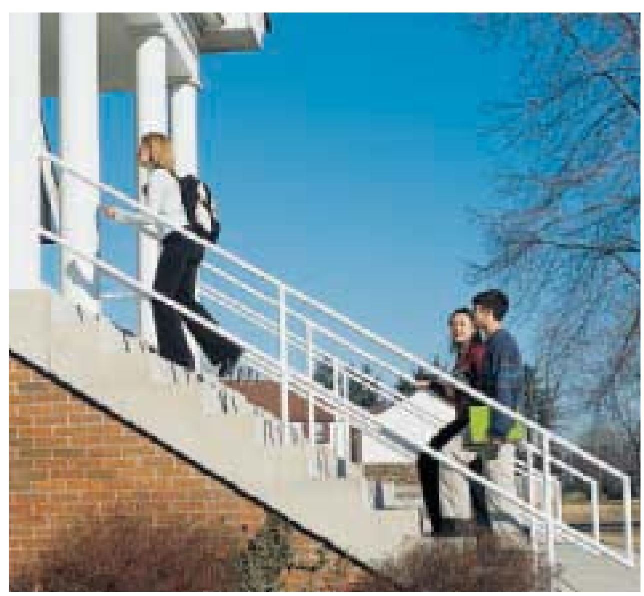
Power $P = \frac{W}{t}$

Power is equal to the work done, divided by the time taken to do the work.

Consider the three students in **Figure 10-6.** The girl hurrying up the stairs is more powerful than the boy who is walking up the stairs. Even though the same work is accomplished by both, the girl accomplishes it in less time and thus develops more power. In the case of the two students walking up the stairs, both accomplish work in the same amount of time.

Power is measured in watts (W). One **watt** is 1 J of energy transferred in 1 s. A watt is a relatively small unit of power. For example, a glass of water weighs about 2 N. If you lift it 0.5 m to your mouth, you do 1 J of work. If you lift the glass in 1 s, you are doing work at the rate of 1 W. Because a watt is such a small unit, power often is measured in kilowatts (kW). One kilowatt is equal to 1000 W.

■ **Figure 10-6** These students are doing work at different rates while climbing the stairs.



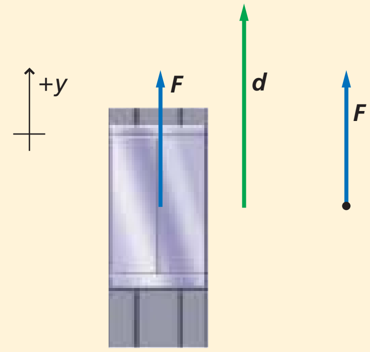
Laura Sifferlin

EXAMPLE Problem 3

Power An electric motor lifts an elevator 9.00 m in 15.0 s by exerting an upward force of 1.20×10^4 N. What power does the motor produce in kW?

1 Analyze and Sketch the Problem

- Sketch the situation showing the elevator with initial conditions.
- Establish a coordinate system with up as positive.
- Draw a vector diagram for the force and displacement.



Known:	Unknown:
$d = 9.00$ m	$P = ?$
$t = 15.0$ s	
$F = 1.20\times10^4$ N	

2 Solve for the Unknown

Solve for power.

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

$$= \frac{Fd}{t}$$ Substitute $W = Fd$

$$= \frac{(1.20\times10^4\ \text{N})(9.00\ \text{m})}{(15.0\ \text{s})}$$ Substitute $F = 1.20\times10^4$ N, $d = 9.00$ m, $t = 15.0$ s

$$= 7.20\ \text{kW}$$

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3 Evaluate the Answer

- **Are the units correct?** Power is measured in J/s.
- **Does the sign make sense?** The positive sign agrees with the upward direction of the force.

PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

9. A box that weighs 575 N is lifted a distance of 20.0 m straight up by a cable attached to a motor. The job is done in 10.0 s. What power is developed by the motor in W and kW?
10. You push a wheelbarrow a distance of 60.0 m at a constant speed for 25.0 s, by exerting a 145-N force horizontally.
    a. What power do you develop?
    b. If you move the wheelbarrow twice as fast, how much power is developed?
11. What power does a pump develop to lift 35 L of water per minute from a depth of 110 m? (1 L of water has a mass of 1.00 kg.)
12. An electric motor develops 65 kW of power as it lifts a loaded elevator 17.5 m in 35 s. How much force does the motor exert?
13. A winch designed to be mounted on a truck, as shown in **Figure 10-7,** is advertised as being able to exert a 6.8×10^3-N force and to develop a power of 0.30 kW. How long would it take the truck and the winch to pull an object 15 m?
14. Your car has stalled and you need to push it. You notice as the car gets going that you need less and less force to keep it going. Suppose that for the first 15 m, your force decreased at a constant rate from 210.0 N to 40.0 N. How much work did you do on the car? Draw a force-displacement graph to represent the work done during this period.

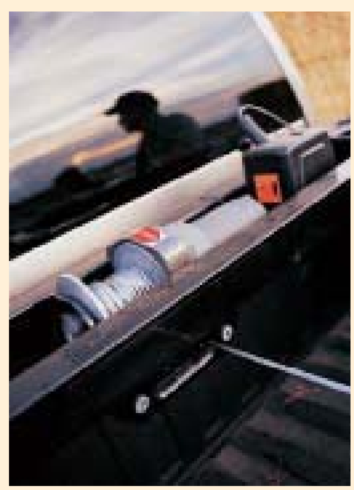


Figure 10-7

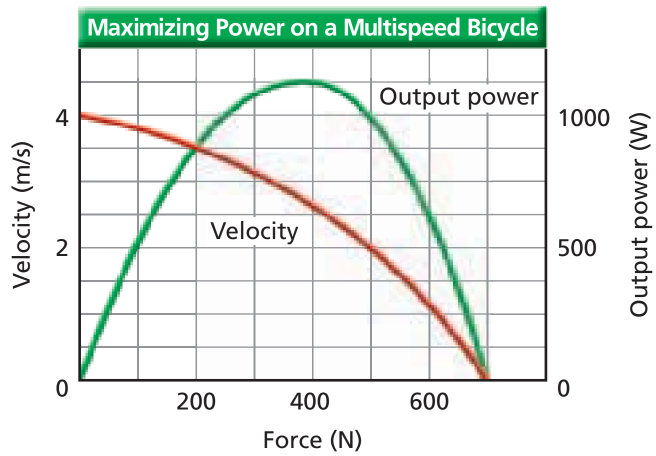


Figure 10-8 When riding a multispeed bicycle, if the muscles in your body exert a force of 400 N and the speed is 2.6 m/s, the power output is over 1000 W.

You may have noticed in Example Problem 3 that when the force and displacement are in the same direction, $P = Fd/t$. However, because the ratio d/t is the speed, power also can be calculated using $P = Fv$.

When you are riding a multispeed bicycle, how do you choose the correct gear? You want to get your body to deliver the largest amount of power. By considering the equation $P = Fv$ you can see that either zero force or zero speed results in no power delivered. The muscles cannot exert extremely large forces, nor can they move very fast. Thus, some combination of moderate force and moderate speed will produce the largest amount of power. **Figure 10-8** shows that in this particular situation, the maximum power output is over 1000 W when the force is about 400 N and speed is about 2.6 m/s. All engines—not just humans—have these limitations. Simple machines often are designed to match the force and speed that the engine can deliver to the needs of the job. You will learn more about simple machines in the next section.

APPLYING PHYSICS

Tour de France A bicyclist in the Tour de France rides at about 8.94 m/s for more than 6 h a day. The power output of the racer is about 1 kW. One-fourth of that power goes into moving the bike against the resistance of the air, gears, and tires. Three-fourths of the power is used to cool the racer's body.

10.1 Section Review

15. Work Murimi pushes a 20-kg mass 10 m across a floor with a horizontal force of 80 N. Calculate the amount of work done by Murimi.

16. Work A mover loads a 185-kg refrigerator into a moving van by pushing it up a 10.0-m, friction-free ramp at an angle of inclination of 11.0°. How much work is done by the mover?

17. Work and Power Does the work required to lift a book to a high shelf depend on how fast you raise it? Does the power required to lift the book depend on how fast you raise it? Explain.

18. Power An elevator lifts a total mass of 1.1×10^3 kg a distance of 40.0 m in 12.5 s. How much power does the elevator generate?

19. Work A 0.180-kg ball falls 2.5 m. How much work does the force of gravity do on the ball?

20. Mass A forklift raises a box 1.2 m and does 7.0 kJ of work on it. What is the mass of the box?

21. Work You and a friend each carry identical boxes from the first floor of a building to a room located on the second floor, farther down the hall. You choose to carry the box first up the stairs, and then down the hall to the room. Your friend carries it down the hall on the first floor, then up a different stairwell to the second floor. Who does more work?

22. Work and Kinetic Energy If the work done on an object doubles its kinetic energy, does it double its velocity? If not, by what ratio does it change the velocity?

23. Critical Thinking Explain how to find the change in energy of a system if three agents exert forces on the system at once.

10.2 Machines

▶ **Objectives**

- **Demonstrate** a knowledge of the usefulness of simple machines.
- **Differentiate** between ideal and real machines in terms of efficiency.
- **Analyze** compound machines in terms of combinations of simple machines.
- **Calculate** efficiencies for simple and compound machines.

▶ **Vocabulary**

machine
effort force
resistance force
mechanical advantage
ideal mechanical advantage
efficiency
compound machine

Everyone uses machines every day. Some are simple tools, such as bottle openers and screwdrivers, while others are complex, such as bicycles and automobiles. Machines, whether powered by engines or people, make tasks easier. A **machine** eases the load by changing either the magnitude or the direction of a force to match the force to the capability of the machine or the person.

Benefits of Machines

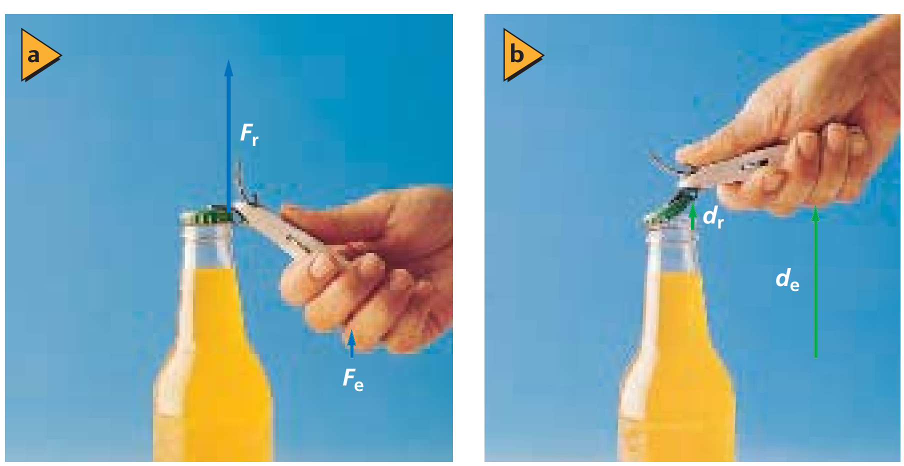
Consider the bottle opener in **Figure 10-9.** When you use the opener, you lift the handle, thereby doing work on the opener. The opener lifts the cap, doing work on it. The work that you do is called the input work, W_i. The work that the machine does is called the output work, W_o.

Recall that work is the transfer of energy by mechanical means. You put work into a machine, such as the bottle opener. That is, you transfer energy to the opener. The opener, in turn, does work on the cap, thereby transferring energy to it. The opener is not a source of energy, and therefore, the cap cannot receive more energy than the amount of energy that you put into the opener. Thus, the output work can never be greater than the input work. The machine simply aids in the transfer of energy from you to the bottle cap.

Mechanical advantage The force exerted by a person on a machine is called the **effort force,** F_e. The force exerted by the machine is called the **resistance force,** F_r. As shown in Figure 10-9a, F_e is the upward force exerted by the person using the bottle opener and F_r is the upward force exerted by the bottle opener. The ratio of resistance force to effort force, F_r/F_e, is called the **mechanical advantage,** *MA*, of the machine.

Mechanical Advantage $MA = \frac{F_r}{F_e}$

The mechanical advantage of a machine is equal to the resistance force divided by the effort force.



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■ **Figure 10-9** A bottle opener is an example of a simple machine. It makes opening a bottle easier, but it does not lessen the work required to do so.

Hutchings Photography

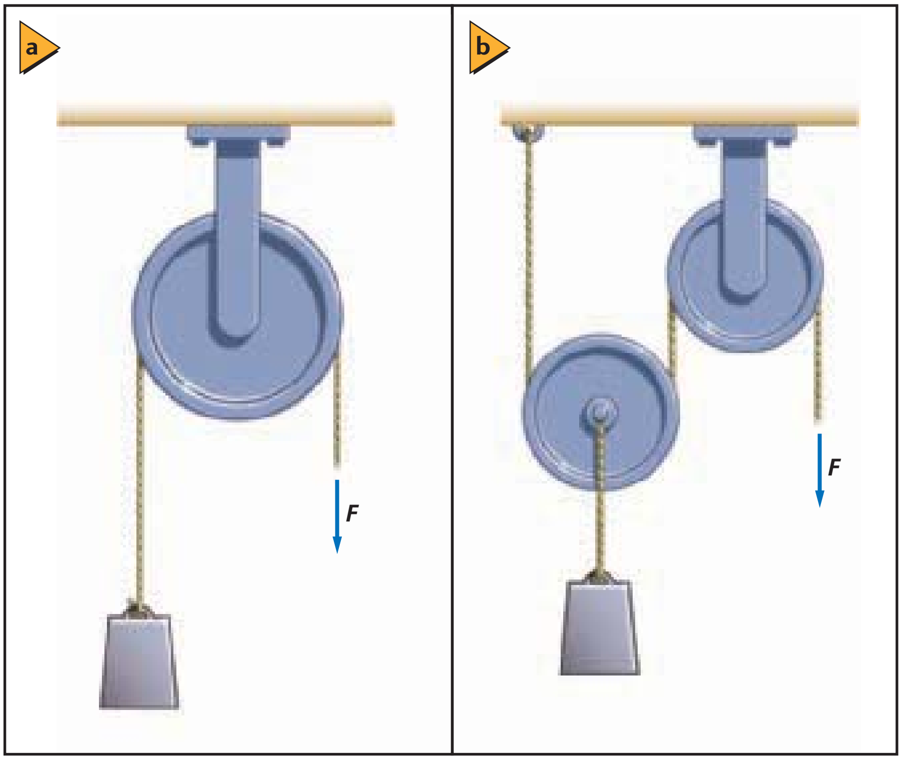

Figure 10-10 A fixed pulley has a mechanical advantage equal to 1 **(a).** A pulley system with a movable pulley has a mechanical advantage greater than 1 **(b).**

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In a fixed pulley, such as the one shown in **Figure 10-10a,** the forces, F_e and F_r, are equal, and consequently *MA* is 1. What is the advantage of this machine? The fixed pulley is useful, not because the effort force is lessened, but because the direction of the effort force is changed. Many machines, such as the bottle opener shown in Figure 10-9 and the pulley system shown in **Figure 10-10b,** have a mechanical advantage greater than 1. When the mechanical advantage is greater than 1, the machine increases the force applied by a person.

You can write the mechanical advantage of a machine in another way using the definition of work. The input work is the product of the effort force that a person exerts, F_e, and the distance his or her hand moved, d_e. In the same way, the output work is the product of the resistance force, F_r, and the displacement of the load, d_r. A machine can increase force, but it cannot increase energy. An ideal machine transfers all the energy, so the output work equals the input work: $W_o = W_i$ or $F_r d_r = F_e d_e$.

This equation can be rewritten $F_r/F_e = d_e/d_r$. Recall that mechanical advantage is given by $MA = F_r/F_e$. Therefore, for an ideal machine, **ideal mechanical advantage,** *IMA*, is equal to the displacement of the effort force, divided by the displacement of the load. The ideal mechanical advantage can be represented by the following equation.

Ideal Mechanical Advantage $IMA = \frac{d_e}{d_r}$

The ideal mechanical advantage of an ideal machine is equal to the displacement of the effort force, divided by the displacement of the load.

Note that you measure the distances moved to calculate the ideal mechanical advantage, but you measure the forces exerted to find the actual mechanical advantage.

Efficiency In a real machine, not all of the input work is available as output work. Energy removed from the system means that there is less output work from the machine. Consequently, the machine is less efficient at accomplishing the task. The **efficiency** of a machine, e, is defined as the ratio of output work to input work.

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Efficiency $e = \frac{W_o}{W_i} \times 100$

The efficiency of a machine (in %) is equal to the output work, divided by the input work, multiplied by 100.

An ideal machine has equal output and input work, $W_o/W_i = 1$, and its efficiency is 100 percent. All real machines have efficiencies of less than 100 percent.

Efficiency can be expressed in terms of the mechanical advantage and ideal mechanical advantage. Efficiency, $e = W_o/W_i$, can be rewritten as follows:

$$\frac{W_o}{W_i} = \frac{F_r d_r}{F_e d_e}$$

Because $MA = F_r/F_e$ and $IMA = d_e/d_r$, the following expression can be written for efficiency.

Efficiency $e = \frac{MA}{IMA} \times 100$

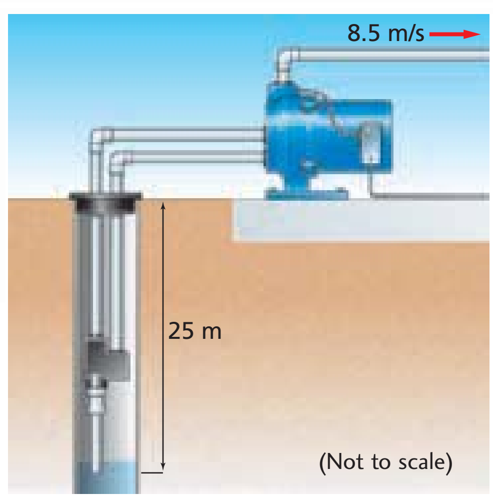
The efficiency of a machine (in %) is equal to its mechanical advantage, divided by the ideal mechanical advantage, multiplied by 100.

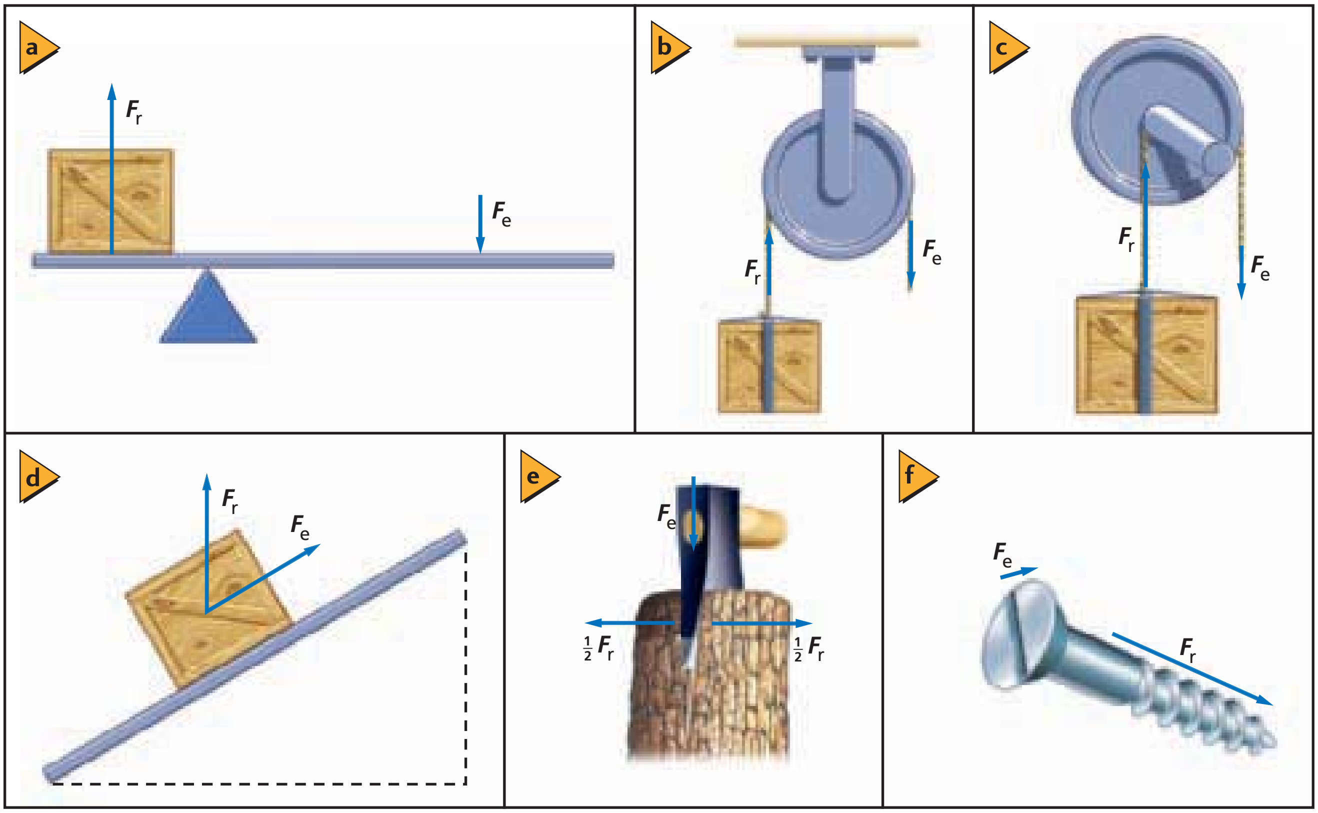
A machine's design determines its ideal mechanical advantage. An efficient machine has an MA almost equal to its IMA. A less-efficient machine has a small MA relative to its IMA. To obtain the same resistance force, a greater force must be exerted in a machine of lower efficiency than in a machine of higher efficiency.

CHALLENGE PROBLEM

An electric pump pulls water at a rate of 0.25 m^3/s from a well that is 25 m deep. The water leaves the pump at a speed of 8.5 m/s.

1. What power is needed to lift the water to the surface?
2. What power is needed to increase the pump's kinetic energy?
3. If the pump's efficiency is 80 percent, how much power must be delivered to the pump?





■ **Figure 10-11** Simple machines include the lever **(a),** pulley **(b),** wheel and axle **(c),** inclined plane **(d),** wedge **(e),** and screw **(f).**

Compound Machines

Most machines, no matter how complex, are combinations of one or more of the six simple machines: the lever, pulley, wheel and axle, inclined plane, wedge, and screw. These machines are shown in **Figure 10-11.**

The *IMA* of all the machines shown in Figure 10-11 is the ratio of distances moved. For machines, such as the lever and the wheel and axle, this ratio can be replaced by the ratio of the distance between the place where the force is applied and the pivot point. A common version of the wheel and axle is a steering wheel, such as the one shown in **Figure 10-12.** The *IMA* is the ratio of the radii of the wheel and axle.

A machine consisting of two or more simple machines linked in such a way that the resistance force of one machine becomes the effort force of the second is called a **compound machine.**

■ **Figure 10-12** The *IMA* for the steering wheel is r_e/r_r.

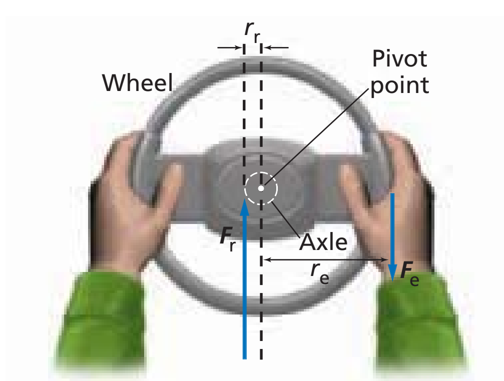


Figure 10-13 A series of simple machines combine to transmit the force that the rider exerts on the pedal to the road.

In a bicycle, the pedal and front gear act like a wheel and axle. The effort force is the force that the rider exerts on the pedal, $F_{rider\ on\ pedal}$. The resistance is the force that the front gear exerts on the chain, $F_{gear\ on\ chain}$, as shown in **Figure 10-13.** The chain exerts an effort force on the rear gear, $F_{chain\ on\ gear}$, equal to the force exerted on the chain. This gear and the rear wheel act like another wheel and axle. The resistance force is the force that the wheel exerts on the road, $F_{wheel\ on\ road}$. According to Newton's third law, the ground exerts an equal forward force on the wheel, which accelerates the bicycle forward.

The *MA* of a compound machine is the product of the *MA*s of the simple machines from which it is made. For example, in the case of the bicycle illustrated in Figure 10-13, the following is true.

$$MA = MA_{machine\ 1} \times MA_{machine\ 2}$$

$$MA = \left(\frac{F_{gear\ on\ chain}}{F_{rider\ on\ pedal}}\right)\left(\frac{F_{wheel\ on\ road}}{F_{chain\ on\ gear}}\right) = \frac{F_{wheel\ on\ road}}{F_{rider\ on\ pedal}}$$

The *IMA* of each wheel-and-axle machine is the ratio of the distances moved.

For the pedal gear, $IMA = \frac{\text{pedal radius}}{\text{front gear radius}}$

For the rear wheel, $IMA = \frac{\text{rear gear radius}}{\text{wheel radius}}$

For the bicycle, then,

$$IMA = \left(\frac{\text{pedal radius}}{\text{front gear radius}}\right)\left(\frac{\text{rear gear radius}}{\text{wheel radius}}\right)$$

$$= \left(\frac{\text{rear gear radius}}{\text{front gear radius}}\right)\left(\frac{\text{pedal radius}}{\text{wheel radius}}\right)$$

Because both gears use the same chain and have teeth of the same size, you can count the number of teeth to find the *IMA*, as follows.

$$IMA = \left(\frac{\text{teeth on rear gear}}{\text{teeth on front gear}}\right)\left(\frac{\text{pedal arm length}}{\text{wheel radius}}\right)$$

Shifting gears on a bicycle is a way of adjusting the ratio of gear radii to obtain the desired *IMA*. You know that if the pedal of a bicycle is at the top or bottom of its circle, no matter how much downward force you exert, the pedal will not turn. The force of your foot is most effective when the force is exerted perpendicular to the arm of the pedal; that is, when the torque is largest. Whenever a force on a pedal is specified, assume that it is applied perpendicular to the arm.

MINI LAB

Wheel and Axle

The gear mechanism on your bicycle multiplies the distance that you travel. What does it do to the force?

1. Mount a wheel and axle system on a sturdy support rod.

2. Wrap a 1-m-long piece of string clockwise around the axle.

3. Wrap another piece of 1-m-long string counterclockwise around the large diameter wheel.

4. Hang a 500-g mass from the end of the string on the larger wheel. ***CAUTION: Avoid dropping the mass.***

5. Pull the string from the axle down so that the mass is lifted by about 10 cm.

Analyze and Conclude

6. What did you notice about the force on the string in your hand?

7. What did you notice about the distance that your hand needed to move to lift the mass? Explain the results in terms of the work done on both strings.

Laura Sifferlin

EXAMPLE Problem 4

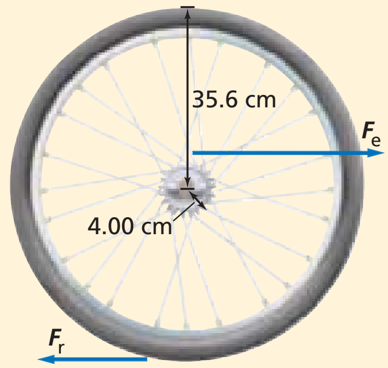
Mechanical Advantage You examine the rear wheel on your bicycle. It has a radius of 35.6 cm and has a gear with a radius of 4.00 cm. When the chain is pulled with a force of 155 N, the wheel rim moves 14.0 cm. The efficiency of this part of the bicycle is 95.0 percent.

a. What is the *IMA* of the wheel and gear?

b. What is the *MA* of the wheel and gear?

c. What is the resistance force?

d. How far was the chain pulled to move the rim 14.0 cm?



1 Analyze and Sketch the Problem

- Sketch the wheel and axle.
- Sketch the force vectors.

Known:		Unknown:	
r_e = 4.00 cm	e = 95.0%	IMA = ?	F_r = ?
r_r = 35.6 cm	d_r = 14.0 cm	MA = ?	d_e = ?
F_e = 155 N			

2 Solve for the Unknown

a. Solve for *IMA*.

$$IMA = \frac{r_e}{r_r}$$

For a wheel-and-axle machine, *IMA* is equal to the ratio of radii.

$$= \frac{4.00\text{ cm}}{35.6\text{ cm}}$$

Substitute r_e = 4.00 cm, r_r = 35.6 cm

$$= 0.112$$

b. Solve for *MA*.

$$e = \frac{MA}{IMA} \times 100$$

$$MA = \left(\frac{e}{100}\right) \times IMA$$

$$= \left(\frac{95.0}{100}\right) \times 0.112$$

Substitute e = 95.0%, IMA = 0.112

$$= 0.106$$

c. Solve for force.

$$MA = \frac{F_r}{F_e}$$

$$F_r = (MA)(F_e)$$

$$= (0.106)(155\text{ N})$$

Substitute MA = 0.106, F_e = 155 N

$$= 16.4\text{ N}$$

d. Solve for distance.

$$IMA = \frac{d_e}{d_r}$$

$$d_e = (IMA)(d_r)$$

$$= (0.112)(14.0\text{ cm})$$

Substitute IMA = 0.112, d_r = 14.0 cm

$$= 1.57\text{ cm}$$

Math Handbook
Isolating a Variable
page 845

3 Evaluate the Answer

- **Are the units correct?** Force is measured in newtons and distance in centimeters.
- **Is the magnitude realistic?** *IMA* is low for a bicycle because a greater F_e is traded for a greater d_r. *MA* is always smaller than *IMA*. Because *MA* is low, F_r also will be low. The small distance the axle moves results in a large distance covered by the wheel. Thus, d_e should be very small.

PRACTICE Problems

- Additional Problems, Appendix B
- Solutions to Selected Problems, Appendix C

24. If the gear radius in the bicycle in Example Problem 4 is doubled, while the force exerted on the chain and the distance the wheel rim moves remain the same, what quantities change, and by how much?

25. A sledgehammer is used to drive a wedge into a log to split it. When the wedge is driven 0.20 m into the log, the log is separated a distance of 5.0 cm. A force of 1.7×10^4 N is needed to split the log, and the sledgehammer exerts a force of 1.1×10^4 N.

a. What is the *IMA* of the wedge?

b. What is the *MA* of the wedge?

c. Calculate the efficiency of the wedge as a machine.

26. A worker uses a pulley system to raise a 24.0-kg carton 16.5 m, as shown in **Figure 10-14.** A force of 129 N is exerted, and the rope is pulled 33.0 m.

a. What is the *MA* of the pulley system?

b. What is the efficiency of the system?

27. You exert a force of 225 N on a lever to raise a 1.25×10^3-N rock a distance of 13 cm. If the efficiency of the lever is 88.7 percent, how far did you move your end of the lever?

28. A winch has a crank with a 45-cm radius. A rope is wrapped around a drum with a 7.5-cm radius. One revolution of the crank turns the drum one revolution.

a. What is the ideal mechanical advantage of this machine?

b. If, due to friction, the machine is only 75 percent efficient, how much force would have to be exerted on the handle of the crank to exert 750 N of force on the rope?

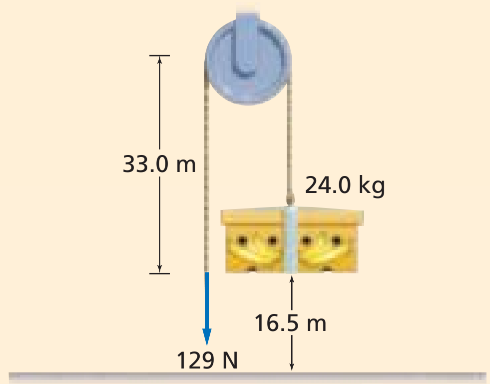


Figure 10-14

Multi-gear bicycle On a multi-gear bicycle, the rider can change the *MA* of the machine by choosing the size of one or both gears. When accelerating or climbing a hill, the rider increases the ideal mechanical advantage to increase the force that the wheel exerts on the road. To increase the *IMA*, the rider needs to make the rear gear radius large compared to the front gear radius (refer to the *IMA* equation on page 270). For the same force exerted by the rider, a larger force is exerted by the wheel on the road. However, the rider must rotate the pedals through more turns for each revolution of the wheel.

On the other hand, less force is needed to ride the bicycle at high speed on a level road. The rider needs to choose a gear that has a small rear gear and a large front gear that will result in a smaller *IMA*. Thus, for the same force exerted by the rider, a smaller force is exerted by the wheel on the road. However, in return, the rider does not have to move the pedals as far for each revolution of the wheel.

An automobile transmission works in the same way. To accelerate a car from rest, large forces are needed and the transmission increases the *IMA*. At high speeds, however, the transmission reduces the *IMA* because smaller forces are needed. Even though the speedometer shows a high speed, the tachometer indicates the engine's low angular speed.

The Human Walking Machine

Movement of the human body is explained by the same principles of force and work that describe all motion. Simple machines, in the form of levers, give humans the ability to walk and run. The lever systems of the human body are complex. However each system has the following four basic parts.

Biology Connection

1. a rigid bar (bone)
2. a source of force (muscle contraction)
3. a fulcrum or pivot (movable joints between bones)
4. a resistance (the weight of the body or an object being lifted or moved)

Figure 10-15 shows the parts of the lever system in a human leg. Lever systems of the body are not very efficient, and mechanical advantages are low. This is why walking and jogging require energy (burn calories) and help people lose weight.

When a person walks, the hip acts as a fulcrum and moves through the arc of a circle, centered on the foot. The center of mass of the body moves as a resistance around the fulcrum in the same arc. The length of the radius of the circle is the length of the lever formed by the bones of the leg. Athletes in walking races increase their velocity by swinging their hips upward to increase this radius. A tall person's body has lever systems with less mechanical advantage than a short person's does. Although tall people usually can walk faster than short people can, a tall person must apply a greater force to move the longer lever formed by the leg bones. How would a tall person do in a walking race? What are the factors that affect a tall person's performance? Walking races are usually 20 or 50 km long. Because of the inefficiency of their lever systems and the length of a walking race, very tall people rarely have the stamina to win.

Figure 10-15 The human walking machine.

10.2 Section Review

29. Simple Machines Classify the tools below as a lever, a wheel and axle, an inclined plane, a wedge, or a pulley.

- **a.** screwdriver
- **b.** pliers
- **c.** chisel
- **d.** nail puller

30. *IMA* A worker is testing a multiple pulley system to estimate the heaviest object that he could lift. The largest downward force he could exert is equal to his weight, 875 N. When the worker moves the rope 1.5 m, the object moves 0.25 m. What is the heaviest object that he could lift?

31. Compound Machines A winch has a crank on a 45-cm arm that turns a drum with a 7.5-cm radius through a set of gears. It takes three revolutions of the crank to rotate the drum through one revolution. What is the *IMA* of this compound machine?

32. Efficiency Suppose you increase the efficiency of a simple machine. Do the *MA* and *IMA* increase, decrease, or remain the same?

33. Critical Thinking The mechanical advantage of a multi-gear bicycle is changed by moving the chain to a suitable rear gear.

- **a.** To start out, you must accelerate the bicycle, so you want to have the bicycle exert the greatest possible force. Should you choose a small or large gear?
- **b.** As you reach your traveling speed, you want to rotate the pedals as few times as possible. Should you choose a small or large gear?
- **c.** Many bicycles also let you choose the size of the front gear. If you want even more force to accelerate while climbing a hill, would you move to a larger or smaller front gear?

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PHYSICS LAB

Stair Climbing and Power

Can you estimate the power you develop as you climb a flight of stairs? Climbing stairs requires energy. As the weight of the body moves through a distance, work is done. Power is a measure of the rate at which work is done. In this activity you will try to maximize the power you develop by applying a vertical force up a flight of stairs over a period of time.

QUESTION

What can you do to increase the power you develop as you climb a flight of stairs?

Objectives

- **Predict** the factors that affect power.
- **Calculate** the power developed.
- **Define** power operationally.
- **Interpret** force, distance, work, time and power data.
- **Make and use graphs** of work versus time, power versus force, and power versus time.

Safety Precautions

- **Avoid wearing loose clothing.**

Materials

meterstick (or tape measure)
stopwatch
bathroom scale

Procedure

1. Measure and record the mass of each person in your group using a bathroom scale. If the scale does not have kilogram units, convert the weight in pounds to kilograms. Recall that 2.2 lbs = 1 kg.
2. Measure the distance from the floor to the top of the flight of stairs you will climb. Record it in the data table.
3. Have each person in your group climb the flight of stairs in a manner that he or she thinks will maximize the power developed.
4. Use your stopwatch to measure the time it takes each person to perform this task. Record your data in the data table.

Horizons Companies

Data Table

Mass (kg)	Weight (N)	Distance (m)	Work Done (J)	Time (s)	Power Generated (W)

Analyze

1. **Calculate** Find each person's weight in newtons and record it in the data table.
2. Calculate the work done by each person.
3. Calculate the power developed by each person in your group as he or she climbs the flight of stairs.
4. **Make and Use Graphs** Use the data you calculated to draw a graph of work versus time and draw the best-fit line.
5. Draw a graph of power versus work and draw the best-fit line.
6. Draw a graph of power versus time and draw the best-fit line.

Conclude and Apply

1. Did each person in your group have the same power rating? Why or why not?
2. Which graph(s) showed a definite relationship between the two variables?
3. Explain why this relationship exists.
4. Write an operational definition of power.

Going Further

1. What three things can be done to increase the power you develop while climbing the flight of stairs?
2. Why were the fastest climbers not necessarily the ones who developed the most power?
3. Why were the members of your group with more mass not necessarily the ones who developed the most power?
4. Compare and contrast your data with those of other groups in your class.

Real-World Physics

1. Research a household appliance that has a power rating equal to or less than the power you developed by climbing the stairs.
2. Suppose an electric power company in your area charges $0.06/kWh. If you charged the same amount for the power you develop climbing stairs, how much money would you earn by climbing stairs for 1 h?
3. If you were designing a stair climbing machine for the local health club, what information would you need to collect? You decide that you will design a stair climbing machine with the ability to calculate the power developed. What information would you have the machine collect in order to let the climber know how much power he or she developed?

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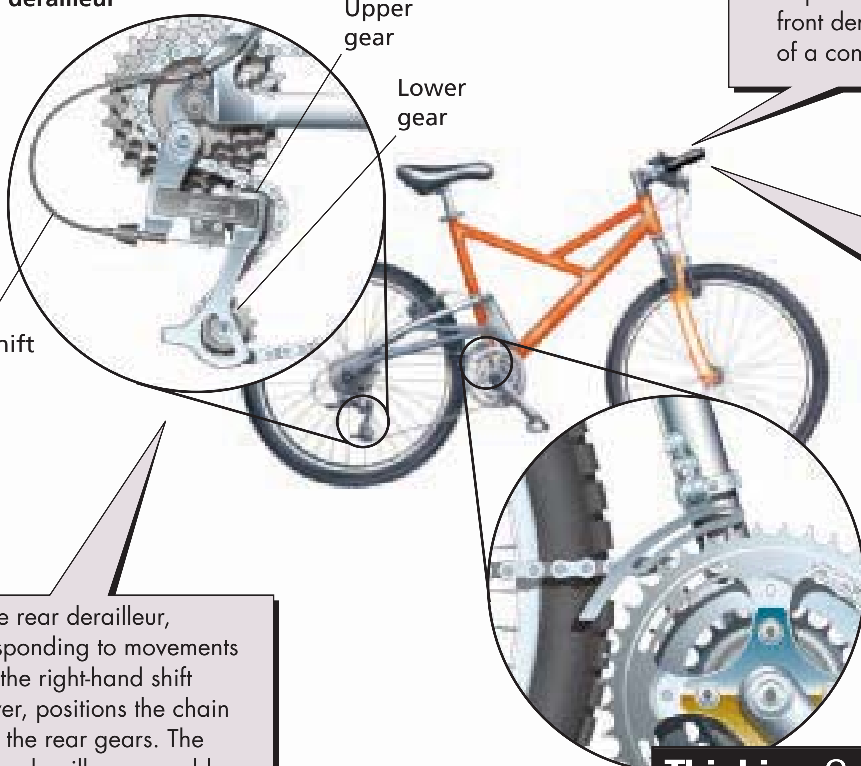
HOW it Works Bicycle Gear Shifters

In a multispeed bicycle with two or three front gears and from five to eight rear gears, front and rear derailleurs (shifters) are employed to position the chain. Changing the combination of front and rear gears varies the *IMA* of the system. A larger *IMA* reduces effort in climbing hills. A lower *IMA* allows for greater speed on level ground, but more effort is required.

$$IMA = \frac{\text{number of teeth on rear gear}}{\text{number of teeth on front gear}}$$



1 The left-hand shift lever adjusts the position of the front derailleur by means of a connecting cable.

2 The right-hand shift lever adjusts the position of the rear derailleur by means of a wire cable routed along the frame from the shift lever to the derailleur.

3 The front derailleur lifts the chain off of the gear teeth and moves it to another gear near it in response to the tightening or loosening of the cable that connects it to the left-hand shift lever.

4 The rear derailleur, responding to movements of the right-hand shift lever, positions the chain on the rear gears. The rear derailleur assembly includes two small gears. The lower gear, tensioned by a spring, keeps the chain tight as it moves from larger to smaller gears. The upper gear moves in or out to position the chain on the gears next to it.

Thinking Critically

1. **Calculate** What is the *IMA* of a multispeed bicycle in the following instances?
   - **a.** when the chain is set on a front gear with 52 teeth and a rear gear with 14 teeth
   - **b.** when the chain is set on a front gear with 42 teeth and a rear gear with 34 teeth
2. **Apply** Which setting in the previous problem, **a** or **b,** would you select to race with a friend on level ground? To climb a steep hill?

Chapter 10

Study Guide

10.1 Energy and Work

Vocabulary

- work (p. 258)
- energy (p. 258)
- kinetic energy (p. 258)
- work-energy theorem (p. 258)
- joule (p. 259)
- power (p. 263)
- watt (p. 263)

Key Concepts

- Work is the transfer of energy by mechanical means.

$$W = Fd$$

- A moving object has kinetic energy.

$$KE = \frac{1}{2}mv^2$$

- The work done on a system is equal to the change in energy of the system.

$$W = \Delta KE$$

- Work is the product of the force exerted on an object and the distance the object moves in the direction of the force.

$$W = Fd \cos \theta$$

- The work done can be determined by calculating the area under a force-displacement graph.
- Power is the rate of doing work, that is the rate at which energy is transferred.

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

10.2 Machines

Vocabulary

- machine (p. 266)
- effort force (p. 266)
- resistance force (p. 266)
- mechanical advantage (p. 266)
- ideal mechanical advantage (p. 267)
- efficiency (p. 268)
- compound machine (p. 269)

Key Concepts

- Machines, whether powered by engines or humans, do not change the amount of work done, but they do make the task easier.
- A machine eases the load, either by changing the magnitude or the direction of the force exerted to do work.
- The mechanical advantage, *MA*, is the ratio of resistance force to effort force.

$$MA = \frac{F_r}{F_e}$$

- The ideal mechanical advantage, *IMA*, is the ratio of the distances moved.

$$IMA = \frac{d_e}{d_r}$$

- The efficiency of a machine is the ratio of output work to input work.

$$e = \frac{W_o}{W_i} \times 100$$

- In all real machines, *MA* is less than *IMA*.
- The efficiency of a machine can by found from the real and ideal mechanical advantages.

$$e = \frac{MA}{IMA} \times 100$$

Chapter 10

Assessment

Concept Mapping

34. Create a concept map using the following terms: *force, displacement, direction of motion, work, change in kinetic energy.*

Mastering Concepts

35. In what units is work measured? (10.1)

36. Suppose a satellite revolves around Earth in a circular orbit. Does Earth's gravity do any work on the satellite? (10.1)

37. An object slides at constant speed on a frictionless surface. What forces act on the object? What work is done by each force? (10.1)

38. Define *work* and *power.* (10.1)

39. What is a watt equivalent to in terms of kilograms, meters, and seconds? (10.1)

40. Is it possible to get more work out of a machine than you put into it? (10.2)

41. Explain how the pedals of a bicycle are a simple machine. (10.2)

Applying Concepts

42. Which requires more work, carrying a 420-N backpack up a 200-m-high hill or carrying a 210-N backpack up a 400-m-high hill? Why?

43. Lifting You slowly lift a box of books from the floor and put it on a table. Earth's gravity exerts a force, magnitude mg, downward, and you exert a force, magnitude mg, upward. The two forces have equal magnitudes and opposite directions. It appears that no work is done, but you know that you did work. Explain what work was done.

44. You have an after-school job carrying cartons of new copy paper up a flight of stairs, and then carrying recycled paper back down the stairs. The mass of the paper does not change. Your physics teacher says that you do not work all day, so you should not be paid. In what sense is the physics teacher correct? What arrangement of payments might you make to ensure that you are properly compensated?

45. You carry the cartons of copy paper down the stairs, and then along a 15-m-long hallway. Are you working now? Explain.

46. Climbing Stairs Two people of the same mass climb the same flight of stairs. The first person climbs the stairs in 25 s; the second person does so in 35 s.

a. Which person does more work? Explain your answer.

b. Which person produces more power? Explain your answer.

47. Show that power delivered can be written as $P = Fv \cos \theta$.

48. How can you increase the ideal mechanical advantage of a machine?

49. Wedge How can you increase the mechanical advantage of a wedge without changing its ideal mechanical advantage?

50. Orbits Explain why a planet orbiting the Sun does not violate the work-energy theorem.

51. Claw Hammer A claw hammer is used to pull a nail from a piece of wood, as shown in **Figure 10-16.** Where should you place your hand on the handle and where should the nail be located in the claw to make the effort force as small as possible?

Figure 10-16

Mastering Problems

10.1 Energy and Work

52. The third floor of a house is 8 m above street level. How much work is needed to move a 150-kg refrigerator to the third floor?

53. Haloke does 176 J of work lifting himself 0.300 m. What is Haloke's mass?

54. Football After scoring a touchdown, an 84.0-kg wide receiver celebrates by leaping 1.20 m off the ground. How much work was done by the wide receiver in the celebration?

55. Tug-of-War During a tug-of-war, team A does 2.20×10^5 J of work in pulling team B 8.00 m. What force was team A exerting?

56. To keep a car traveling at a constant velocity, a 551-N force is needed to balance frictional forces. How much work is done against friction by the car as it travels from Columbus to Cincinnati, a distance of 161 km?

 For more problems, go to Additional Problems, Appendix B.

57. **Cycling** A cyclist exerts a force of 15.0 N as he rides a bike 251 m in 30.0 s. How much power does the cyclist develop?

58. A student librarian lifts a 2.2-kg book from the floor to a height of 1.25 m. He carries the book 8.0 m to the stacks and places the book on a shelf that is 0.35 m above the floor. How much work does he do on the book?

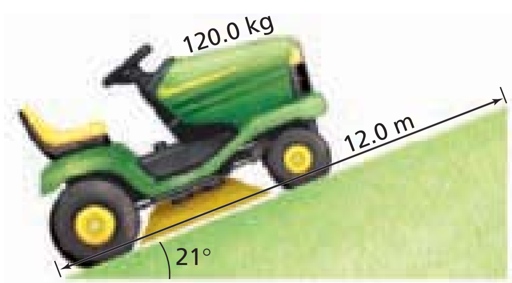
59. A force of 300.0 N is used to push a 145-kg mass 30.0 m horizontally in 3.00 s.
   a. Calculate the work done on the mass.
   b. Calculate the power developed.

60. **Wagon** A wagon is pulled by a force of 38.0 N exerted on the handle at an angle of 42.0° with the horizontal. If the wagon is pulled in a circle of radius 25.0 m, how much work is done?

61. **Lawn Mower** Shani is pushing a lawn mower with a force of 88.0 N along a handle that makes an angle of 41.0° with the horizontal. How much work is done by Shani in moving the lawn mower 1.2 km to mow the yard?

62. A 17.0-kg crate is to be pulled a distance of 20.0 m, requiring 1210 J of work to be done. If the job is done by attaching a rope and pulling with a force of 75.0 N, at what angle is the rope held?

63. **Lawn Tractor** A 120-kg lawn tractor, shown in **Figure 10-17,** goes up a 21° incline that is 12.0 m long in 2.5 s. Calculate the power that is developed by the tractor.



■ **Figure 10-17**

64. You slide a crate up a ramp at an angle of 30.0° by exerting a 225-N force parallel to the ramp. The crate moves at a constant speed. The coefficient of friction is 0.28. How much work did you do on the crate as it was raised a vertical distance of 1.15 m?

65. **Piano** A 4.2×10^3-N piano is to be slid up a 3.5-m frictionless plank at a constant speed. The plank makes an angle of 30.0° with the horizontal. Calculate the work done by the person sliding the piano up the plank.

66. **Sled** Diego pulls a 4.5-kg sled across level snow with a force of 225 N on a rope that is 35.0° above the horizontal, as shown in **Figure 10-18.** If the sled moves a distance of 65.3 m, how much work does Diego do?

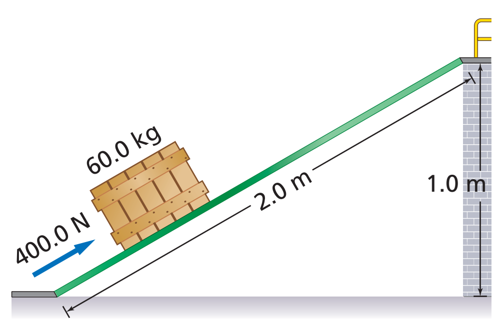
■ **Figure 10-18**

67. **Escalator** Sau-Lan has a mass of 52 kg. She rides up the escalator at Ocean Park in Hong Kong. This is the world's longest escalator, with a length of 227 m and an average inclination of 31°. How much work does the escalator do on Sau-Lan?

68. **Lawn Roller** A lawn roller is pushed across a lawn by a force of 115 N along the direction of the handle, which is 22.5° above the horizontal. If 64.6 W of power is developed for 90.0 s, what distance is the roller pushed?

69. John pushes a crate across the floor of a factory with a horizontal force. The roughness of the floor changes, and John must exert a force of 20 N for 5 m, then 35 N for 12 m, and then 10 N for 8 m.
   a. Draw a graph of force as a function of distance.
   b. Find the work John does pushing the crate.

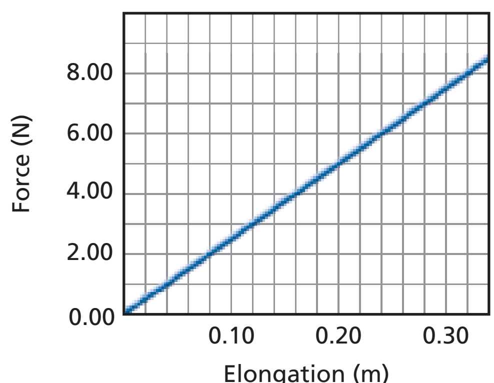
70. Maricruz slides a 60.0-kg crate up an inclined ramp that is 2.0-m long and attached to a platform 1.0 m above floor level, as shown in **Figure 10-19.** A 400.0-N force, parallel to the ramp, is needed to slide the crate up the ramp at a constant speed.
   a. How much work does Maricruz do in sliding the crate up the ramp?
   b. How much work would be done if Maricruz simply lifted the crate straight up from the floor to the platform?



■ **Figure 10-19**

71. Boat Engine An engine moves a boat through the water at a constant speed of 15 m/s. The engine must exert a force of 6.0 kN to balance the force that the water exerts against the hull. What power does the engine develop?

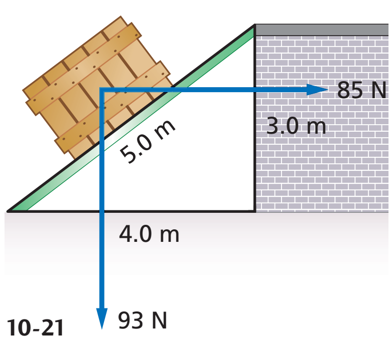
72. In **Figure 10-20,** the magnitude of the force necessary to stretch a spring is plotted against the distance the spring is stretched.
a. Calculate the slope of the graph, k, and show that $F = kd$, where $k = 25$ N/m.
b. Find the amount of work done in stretching the spring from 0.00 m to 0.20 m by calculating the area under the graph from 0.00 m to 0.20 m.
c. Show that the answer to part **b** can be calculated using the formula $W = \frac{1}{2}kd^2$, where W is the work, $k = 25$ N/m (the slope of the graph), and d is the distance the spring is stretched (0.20 m).



■ **Figure 10-20**

73. Use the graph in Figure 10-20 to find the work needed to stretch the spring from 0.12 m to 0.28 m.

74. A worker pushes a crate weighing 93 N up an inclined plane. The worker pushes the crate horizontally, parallel to the ground, as illustrated in **Figure 10-21.**
a. The worker exerts a force of 85 N. How much work does he do?
b. How much work is done by gravity? (Be careful with the signs you use.)
c. The coefficient of friction is $\mu = 0.20$. How much work is done by friction? (Be careful with the signs you use.)



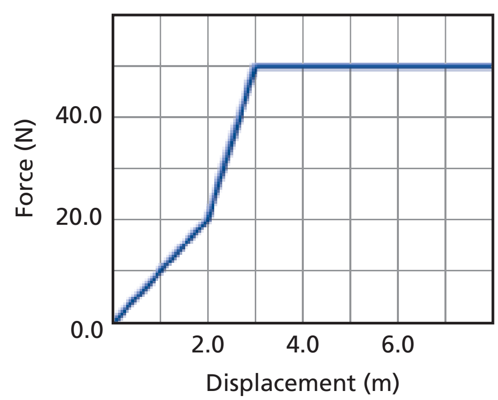
■ **Figure 10-21**

75. Oil Pump In 35.0 s, a pump delivers 0.550 m^3 of oil into barrels on a platform 25.0 m above the intake pipe. The oil's density is 0.820 g/cm^3.
a. Calculate the work done by the pump.
b. Calculate the power produced by the pump.

76. Conveyor Belt A 12.0-m-long conveyor belt, inclined at 30.0°, is used to transport bundles of newspapers from the mail room up to the cargo bay to be loaded onto delivery trucks. Each newspaper has a mass of 1.0 kg, and there are 25 newspapers per bundle. Determine the power that the conveyor develops if it delivers 15 bundles per minute.

77. A car is driven at a constant speed of 76 km/h down a road. The car's engine delivers 48 kW of power. Calculate the average force that is resisting the motion of the car.

78. The graph in **Figure 10-22** shows the force and displacement of an object being pulled.
a. Calculate the work done to pull the object 7.0 m.
b. Calculate the power that would be developed if the work was done in 2.0 s.



■ **Figure 10-22**

10.2 Machines

79. Piano Takeshi raises a 1200-N piano a distance of 5.00 m using a set of pulleys. He pulls in 20.0 m of rope.
a. How much effort force would Takeshi apply if this were an ideal machine?
b. What force is used to balance the friction force if the actual effort is 340 N?
c. What is the output work?
d. What is the input work?
e. What is the mechanical advantage?

80. Lever Because there is very little friction, the lever is an extremely efficient simple machine. Using a 90.0-percent-efficient lever, what input work is required to lift an 18.0-kg mass through a distance of 0.50 m?

 For more problems, go to Additional Problems, Appendix B.

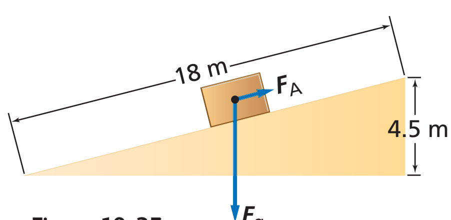
81. A pulley system lifts a 1345-N weight a distance of 0.975 m. Paul pulls the rope a distance of 3.90 m, exerting a force of 375 N.
a. What is the ideal mechanical advantage of the system?
b. What is the mechanical advantage?
c. How efficient is the system?

82. A force of 1.4 N is exerted through a distance of 40.0 cm on a rope in a pulley system to lift a 0.50-kg mass 10.0 cm. Calculate the following.
a. the *MA*
b. the *IMA*
c. the efficiency

83. A student exerts a force of 250 N on a lever, through a distance of 1.6 m, as he lifts a 150-kg crate. If the efficiency of the lever is 90.0 percent, how far is the crate lifted?

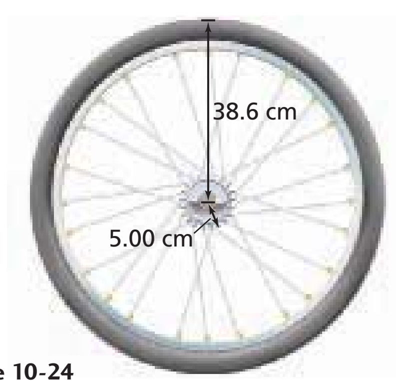
84. What work is required to lift a 215-kg mass a distance of 5.65 m, using a machine that is 72.5 percent efficient?

85. The ramp in **Figure 10-23** is 18 m long and 4.5 m high.
a. What force, parallel to the ramp (F_A), is required to slide a 25-kg box at constant speed to the top of the ramp if friction is disregarded?
b. What is the *IMA* of the ramp?
c. What are the real *MA* and the efficiency of the ramp if a parallel force of 75 N is actually required?



■ **Figure 10-23**

86. Bicycle Luisa pedals a bicycle with a gear radius of 5.00 cm and a wheel radius of 38.6 cm, as shown in **Figure 10-24.** If the wheel revolves once, what is the length of the chain that was used?



■ **Figure 10-24**

87. Crane A motor with an efficiency of 88 percent operates a crane with an efficiency of 42 percent. If the power supplied to the motor is 5.5 kW, with what constant speed does the crane lift a 410-kg crate of machine parts?

88. A compound machine is constructed by attaching a lever to a pulley system. Consider an ideal compound machine consisting of a lever with an *IMA* of 3.0 and a pulley system with an *IMA* of 2.0.
a. Show that the IMA of this compound machine is 6.0.
b. If the compound machine is 60.0 percent efficient, how much effort must be applied to the lever to lift a 540-N box?
c. If you move the effort side of the lever 12.0 cm, how far is the box lifted?

Mixed Review

89. Ramps Isra has to get a piano onto a 2.0-m-high platform. She can use a 3.0-m-long frictionless ramp or a 4.0-m-long frictionless ramp. Which ramp should Isra use if she wants to do the least amount of work?

90. Brutus, a champion weightlifter, raises 240 kg of weights a distance of 2.35 m.
a. How much work is done by Brutus lifting the weights?
b. How much work is done by Brutus holding the weights above his head?
c. How much work is done by Brutus lowering them back to the ground?
d. Does Brutus do work if he lets go of the weights and they fall back to the ground?
e. If Brutus completes the lift in 2.5 s, how much power is developed?

91. A horizontal force of 805 N is needed to drag a crate across a horizontal floor with a constant speed. You drag the crate using a rope held at an angle of 32°.
a. What force do you exert on the rope?
b. How much work do you do on the crate if you move it 22 m?
c. If you complete the job in 8.0 s, what power is developed?

92. Dolly and Ramp A mover's dolly is used to transport a refrigerator up a ramp into a house. The refrigerator has a mass of 115 kg. The ramp is 2.10 m long and rises 0.850 m. The mover pulls the dolly with a force of 496 N up the ramp. The dolly and ramp constitute a machine.
a. What work does the mover do?
b. What is the work done on the refrigerator by the machine?
c. What is the efficiency of the machine?

93. Sally does 11.4 kJ of work dragging a wooden crate 25.0 m across a floor at a constant speed. The rope makes an angle of 48.0° with the horizontal.
- **a.** How much force does the rope exert on the crate?
- **b.** What is the force of friction acting on the crate?
- **c.** What work is done by the floor through the force of friction between the floor and the crate?

94. **Sledding** An 845-N sled is pulled a distance of 185 m. The task requires 1.20×10^4 J of work and is done by pulling on a rope with a force of 125 N. At what angle is the rope held?

95. An electric winch pulls an 875-N crate up a 15° incline at 0.25 m/s. The coefficient of friction between the crate and incline is 0.45.
- **a.** What power does the winch develop?
- **b.** If the winch is 85 percent efficient, what is the electrical power that must be delivered to the winch?

Thinking Critically

96. **Analyze and Conclude** You work at a store, carrying boxes to a storage loft that is 12 m above the ground. You have 30 boxes with a total mass of 150 kg that must be moved as quickly as possible, so you consider carrying more than one up at a time. If you try to move too many at once, you know that you will go very slowly, resting often. If you carry only one box at a time, most of the energy will go into raising your own body. The power (in watts) that your body can develop over a long time depends on the mass that you carry, as shown in **Figure 10-25.** This is an example of a power curve that applies to machines as well as to people. Find the number of boxes to carry on each trip that would minimize the time required. What time would you spend doing the job? Ignore the time needed to go back down the stairs and to lift and lower each box.

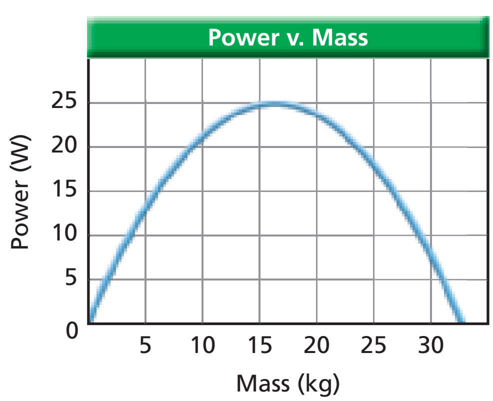


Figure 10-25

97. **Apply Concepts** A sprinter of mass 75 kg runs the 50.0-m dash in 8.50 s. Assume that the sprinter's acceleration is constant throughout the race.
- **a.** What is the average power of the sprinter over the 50.0 m?
- **b.** What is the maximum power generated by the sprinter?
- **c.** Make a quantitative graph of power versus time for the entire race.

98. **Apply Concepts** The sprinter in the previous problem runs the 50.0-m dash in the same time, 8.50 s. However, this time the sprinter accelerates in the first second and runs the rest of the race at a constant velocity.
- **a.** Calculate the average power produced for that first second.
- **b.** What is the maximum power that the sprinter now generates?

Writing in Physics

99. Just as a bicycle is a compound machine, so is an automobile. Find the efficiencies of the component parts of the power train (engine, transmission, wheels, and tires). Explore possible improvements in each of these efficiencies.

100. The terms *force, work, power,* and *energy* often mean the same thing in everyday use. Obtain examples from advertisements, print media, radio, and television that illustrate meanings for these terms that differ from those used in physics.

Cumulative Review

101. You are helping your grandmother with some gardening and have filled a garbage can with weeds and soil. Now you have to move the garbage can across the yard and realize it is so heavy that you will need to push it, rather than lift it. If the can has a mass of 24 kg, the coefficient of kinetic friction between the can's bottom and the muddy grass is 0.27, and the coefficient of static friction between those same surfaces is 0.35, how hard do you have to push horizontally to get the can to just start moving? (Chapter 5)

102. **Baseball** If a major league pitcher throws a fastball horizontally at a speed of 40.3 m/s (90 mph) and it travels 18.4 m (60 ft, 6 in), how far has it dropped by the time it crosses home plate? (Chapter 6)

103. People sometimes say that the Moon stays in its orbit because the "centrifugal force just balances the centripetal force, giving no net force." Explain why this idea is wrong. (Chapter 8)

 For more problems, go to Additional Problems, Appendix B.

Standardized Test Practice

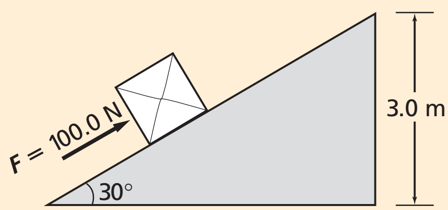
Multiple Choice

1. A pulley system consists of two fixed pulleys and two movable pulleys that lift a load that has a weight of 300 N. If the effort force used to lift the load is 100 N, what is the mechanical advantage of the system?

- (A) $\frac{1}{3}$
- (B) $\frac{3}{4}$
- (C) 3
- (D) 6

2. The box in the diagram is being pushed up the ramp with a force of 100.0 N. If the height of the ramp is 3.0 m, what is the work done on the box? (sin 30° = 0.50, cos 30° = 0.87, tan 30° = 0.58)

- (A) 150 J
- (B) 260 J
- (C) 450 J
- (D) 600 J



3. A compound machine used to raise heavy boxes consists of a ramp and a pulley. The efficiency of pulling a 100-kg box up the ramp is 50%. If the efficiency of the pulley is 90%, what is the overall efficiency of the compound machine?

- (A) 40%
- (B) 45%
- (C) 50%
- (D) 70%

4. A skater with a mass of 50.0 kg slides across an icy pond with negligible friction. As he approaches a friend, both he and his friend hold out their hands, and the friend exerts a force in the direction opposite to the skater's movement, which slows the skater's speed from 2.0 m/s^2 to 1.0 m/s^2. What is the change in the skater's kinetic energy?

- (A) 25 J
- (B) 75 J
- (C) 100 J
- (D) 150 J

5. A 20.0-N block is attached to the end of a rope, and the rope is looped around a pulley system. If you pull the opposite end of the rope a distance of 2.00 m, the pulley system raises the block a distance of 0.40 m. What is the pulley system's ideal mechanical advantage?

- (A) 2.5
- (B) 4.0
- (C) 5.0
- (D) 10.0

6. Two people carry identical 40.0-N boxes up a ramp. The ramp is 2.00 m long and rests on a platform that is 1.00 m high. One person walks up the ramp in 2.00 s, and the other person walks up the ramp in 4.00 s. What is the difference in power the two people use to carry the boxes up the ramp?

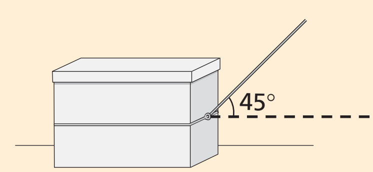
- (A) 5.00 W
- (B) 10.0 W
- (C) 20.0 W
- (D) 40.0 W

7. A 4-N soccer ball sits motionless on a field. A player's foot exerts a force of 5 N on the ball for a distance of 0.1 m, and the ball rolls a distance of 10 m. How much kinetic energy does the ball gain from the player?

- (A) 0.5 J
- (B) 0.9 J
- (C) 9 J
- (D) 50 J

Extended Answer

8. The diagram shows a box being pulled by a rope with a force of 200.0 N along a horizontal surface. The angle the rope makes with the horizontal is 45°. Calculate the work done on the box and the power required to pull it a distance of 5.0 m in 10.0 s. (sin 45° = cos 45° = 0.7)



✓ Test-Taking TIP

Beat the Clock and then Go Back

As you take a practice test, pace yourself to finish each section just a few minutes early so you can go back and check over your work.