

## CHAPTER 9

# Work, Energy, and Simple Machines



**Figure 9.1** People on a roller coaster experience thrills caused by changes in types of energy. (Jonrev, Wikimedia Commons)

### Chapter Outline

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#### [9.1 Work, Power, and the Work–Energy Theorem](#)

#### [9.2 Mechanical Energy and Conservation of Energy](#)

#### [9.3 Simple Machines](#)

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**INTRODUCTION** Roller coasters have provided thrills for daring riders around the world since the nineteenth century. Inventors of roller coasters used simple physics to build the earliest examples using railroad tracks on mountainsides and old mines. Modern roller coaster designers use the same basic laws of physics to create the latest amusement park favorites. Physics principles are used to engineer the machines that do the work to lift a roller coaster car up its first big incline before it is set loose to roll. Engineers also have to understand the changes in the car's energy that keep it speeding over hills, through twists, turns, and even loops.

What exactly is energy? How can changes in force, energy, and simple machines move objects like roller coaster cars? How can machines help us do work? In this chapter, you will discover the answer to this question and many more, as you learn about

work, energy, and simple machines.

## 9.1 Work, Power, and the Work–Energy Theorem

### Section Learning Objectives

*By the end of this section, you will be able to do the following:*

- Describe and apply the work–energy theorem
- Describe and calculate work and power

### Section Key Terms

energy	gravitational potential energy	joule	kinetic energy	mechanical energy
potential energy	power	watt	work	work–energy theorem

### The Work–Energy Theorem

In physics, the term **work** has a very specific definition. Work is application of force,  $\mathbf{f}$ , to move an object over a distance,  $d$ , in the direction that the force is applied. Work,  $W$ , is described by the equation

$$W = \mathbf{f}d.$$

Some things that we typically consider to be work are not work in the scientific sense of the term. Let's consider a few examples. Think about why each of the following statements is true.

- Homework *is not* work.
- Lifting a rock upwards off the ground *is* work.
- Carrying a rock in a straight path across the lawn at a constant speed *is not* work.

The first two examples are fairly simple. Homework is not work because objects are not being moved over a distance. Lifting a rock up off the ground is work because the rock is moving in the direction that force is applied. The last example is less obvious. Recall from the laws of motion that force is *not* required to move an object at constant velocity. Therefore, while some force may be applied to keep the rock up off the ground, no net force is applied to keep the rock moving forward at constant velocity.

Work and **energy** are closely related. When you do work to move an object, you change the object's energy. You (or an object) also expend energy to do work. In fact, energy can be defined as the ability to do work. Energy can take a variety of different forms, and one form of energy can transform to another. In this chapter we will be concerned with **mechanical energy**, which comes in two forms: **kinetic energy** and **potential energy**.

- Kinetic energy is also called energy of motion. A moving object has kinetic energy.
- Potential energy, sometimes called stored energy, comes in several forms. **Gravitational potential energy** is the stored energy an object has as a result of its position above Earth's surface (or another object in space). A roller coaster car at the top of a hill has gravitational potential energy.

Let's examine how doing work on an object changes the object's energy. If we apply force to lift a rock off the ground, we increase the rock's potential energy,  $PE$ . If we drop the rock, the force of gravity increases the rock's kinetic energy as the rock moves downward until it hits the ground.

The force we exert to lift the rock is equal to its weight,  $w$ , which is equal to its mass,  $m$ , multiplied by acceleration due to gravity,  $g$ .

$$\mathbf{f} = w = mg$$

The work we do on the rock equals the force we exert multiplied by the distance,  $d$ , that we lift the rock. The work we do on the rock also equals the rock's gain in gravitational potential energy,  $PE_e$ .

$$W = PE_e = \mathbf{f}mg$$

Kinetic energy depends on the mass of an object and its velocity,  $\mathbf{v}$ .

$$KE = \frac{1}{2}m\mathbf{v}^2$$

When we drop the rock the force of gravity causes the rock to fall, giving the rock kinetic energy. When work done on an object increases only its kinetic energy, then the net work equals the change in the value of the quantity  $\frac{1}{2}mv^2$ . This is a statement of the **work–energy theorem**, which is expressed mathematically as

$$W = \Delta KE = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2.$$

The subscripts <sub>2</sub> and <sub>1</sub> indicate the final and initial velocity, respectively. This theorem was proposed and successfully tested by James Joule, shown in [Figure 9.2](#).

Does the name Joule sound familiar? The **joule** (J) is the metric unit of measurement for both work and energy. The measurement of work and energy with the same unit reinforces the idea that work and energy are related and can be converted into one another.  $1.0 \text{ J} = 1.0 \text{ N} \cdot \text{m}$ , the units of force multiplied by distance.  $1.0 \text{ N} = 1.0 \text{ kg} \cdot \text{m/s}^2$ , so  $1.0 \text{ J} = 1.0 \text{ kg} \cdot \text{m}^2/\text{s}^2$ . Analyzing the units of the term  $(1/2)mv^2$  will produce the same units for joules.



**Figure 9.2** The joule is named after physicist James Joule (1818–1889). (C. H. Jeens, Wikimedia Commons)



## WATCH PHYSICS

### Work and Energy

This video explains the work energy theorem and discusses how work done on an object increases the object's KE.

[Click to view content \(https://www.khanacademy.org/embed\\_video?v=2WS1sG9fhOk\)](https://www.khanacademy.org/embed_video?v=2WS1sG9fhOk)

#### GRASP CHECK

True or false—The energy increase of an object acted on only by a gravitational force is equal to the product of the object's weight and the distance the object falls.

- True
- False

## Calculations Involving Work and Power

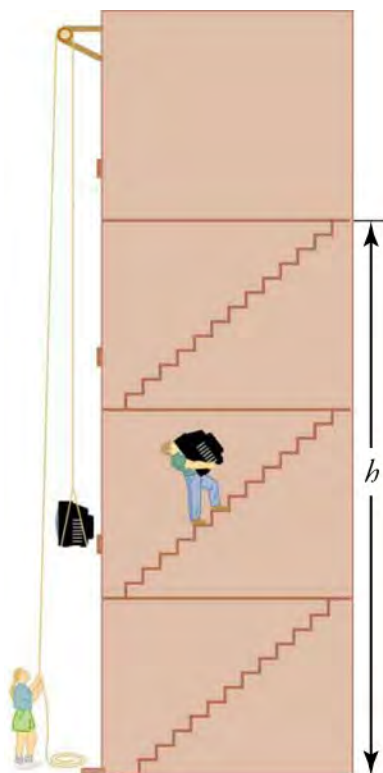
In applications that involve work, we are often interested in how fast the work is done. For example, in roller coaster design, the amount of time it takes to lift a roller coaster car to the top of the first hill is an important consideration. Taking a half hour on the ascent will surely irritate riders and decrease ticket sales. Let's take a look at how to calculate the time it takes to do work.

Recall that a rate can be used to describe a quantity, such as work, over a period of time. **Power** is the rate at which work is done. In this case, rate means *per unit of time*. Power is calculated by dividing the work done by the time it took to do the work.

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

Let's consider an example that can help illustrate the differences among work, force, and power. Suppose the woman in [Figure 9.3](#) lifting the TV with a pulley gets the TV to the fourth floor in two minutes, and the man carrying the TV up the stairs takes five

minutes to arrive at the same place. They have done the same amount of work ( $\mathbf{fd}$ ) on the TV, because they have moved the same mass over the same vertical distance, which requires the same amount of upward force. However, the woman using the pulley has generated more power. This is because she did the work in a shorter amount of time, so the denominator of the power formula,  $t$ , is smaller. (For simplicity's sake, we will leave aside for now the fact that the man climbing the stairs has also done work on himself.)



**Figure 9.3** No matter how you move a TV to the fourth floor, the amount of work performed and the potential energy gain are the same.

Power can be expressed in units of **watts** (W). This unit can be used to measure power related to any form of energy or work. You have most likely heard the term used in relation to electrical devices, especially light bulbs. Multiplying power by time gives the amount of energy. Electricity is sold in kilowatt-hours because that equals the amount of electrical energy consumed.

The watt unit was named after James Watt (1736–1819) (see [Figure 9.4](#)). He was a Scottish engineer and inventor who discovered how to coax more power out of steam engines.



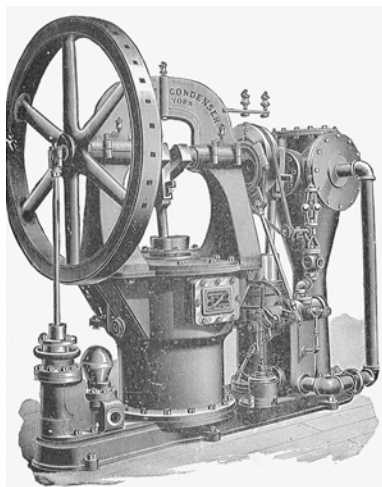
**Figure 9.4** Is James Watt thinking about watts? (Carl Frederik von Breda, Wikimedia Commons)



## LINKS TO PHYSICS

### Watt's Steam Engine

James Watt did not invent the steam engine, but by the time he was finished tinkering with it, it was more useful. The first steam engines were not only inefficient, they only produced a back and forth, or reciprocal, motion. This was natural because pistons move in and out as the pressure in the chamber changes. This limitation was okay for simple tasks like pumping water or mashing potatoes, but did not work so well for moving a train. Watt was able to build a steam engine that converted reciprocal motion to circular motion. With that one innovation, the industrial revolution was off and running. The world would never be the same. One of Watt's steam engines is shown in [Figure 9.5](#). The video that follows the figure explains the importance of the steam engine in the industrial revolution.



**Figure 9.5** A late version of the Watt steam engine. (Nehemiah Hawkins, Wikimedia Commons)

## WATCH PHYSICS

### Watt's Role in the Industrial Revolution

This video demonstrates how the watts that resulted from Watt's inventions helped make the industrial revolution possible and allowed England to enter a new historical era.

[Click to view content \(https://www.youtube.com/embed/zhL5DCizj5c\)](https://www.youtube.com/embed/zhL5DCizj5c)

#### GRASP CHECK

Which form of mechanical energy does the steam engine generate?

- Potential energy
- Kinetic energy
- Nuclear energy
- Solar energy

Before proceeding, be sure you understand the distinctions among force, work, energy, and power. Force exerted on an object over a distance does work. Work can increase energy, and energy can do work. Power is the rate at which work is done.

## WORKED EXAMPLE

### Applying the Work–Energy Theorem

An ice skater with a mass of 50 kg is gliding across the ice at a speed of 8 m/s when her friend comes up from behind and gives her a push, causing her speed to increase to 12 m/s. How much work did the friend do on the skater?

**Strategy**

The work–energy theorem can be applied to the problem. Write the equation for the theorem and simplify it if possible.

$$W = \Delta KE = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2$$

$$\text{Simplify to } W = \frac{1}{2}m(v_2^2 - v_1^2)$$

**Solution**

Identify the variables.  $m = 50 \text{ kg}$ ,

$$v_2 = 12 \frac{\text{m}}{\text{s}}, \text{ and } v_1 = 8 \frac{\text{m}}{\text{s}}$$

9.1

Substitute.

$$W = \frac{1}{2}50(12^2 - 8^2) = 2,000 \text{ J}$$

9.2

**Discussion**

Work done on an object or system increases its energy. In this case, the increase is to the skater's kinetic energy. It follows that the increase in energy must be the difference in KE before and after the push.

**TIPS FOR SUCCESS**

This problem illustrates a general technique for approaching problems that require you to apply formulas: Identify the unknown and the known variables, express the unknown variables in terms of the known variables, and then enter all the known values.

## Practice Problems

- How much work is done when a weightlifter lifts a 200 N barbell from the floor to a height of 2 m?
  - 0 J
  - 100 J
  - 200 J
  - 400 J
- Identify which of the following actions generates more power. Show your work.
  - carrying a 100 N TV to the second floor in 50 s or
  - carrying a 24 N watermelon to the second floor in 10 s?
  - Carrying a 100 N TV generates more power than carrying a 24 N watermelon to the same height because power is defined as work done times the time interval.
  - Carrying a 100 N TV generates more power than carrying a 24 N watermelon to the same height because power is defined as the ratio of work done to the time interval.
  - Carrying a 24 N watermelon generates more power than carrying a 100 N TV to the same height because power is defined as work done times the time interval.
  - Carrying a 24 N watermelon generates more power than carrying a 100 N TV to the same height because power is defined as the ratio of work done and the time interval.

## Check Your Understanding

- Identify two properties that are expressed in units of joules.
  - work and force
  - energy and weight
  - work and energy
  - weight and force

4. When a coconut falls from a tree, work  $W$  is done on it as it falls to the beach. This work is described by the equation

$$W = Fd = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2.$$

9.3

Identify the quantities  $F$ ,  $d$ ,  $m$ ,  $v_1$ , and  $v_2$  in this event.

- $F$  is the force of gravity, which is equal to the weight of the coconut,  $d$  is the distance the nut falls,  $m$  is the mass of the earth,  $v_1$  is the initial velocity, and  $v_2$  is the velocity with which it hits the beach.
- $F$  is the force of gravity, which is equal to the weight of the coconut,  $d$  is the distance the nut falls,  $m$  is the mass of the coconut,  $v_1$  is the initial velocity, and  $v_2$  is the velocity with which it hits the beach.
- $F$  is the force of gravity, which is equal to the weight of the coconut,  $d$  is the distance the nut falls,  $m$  is the mass of the earth,  $v_1$  is the velocity with which it hits the beach, and  $v_2$  is the initial velocity.
- $F$  is the force of gravity, which is equal to the weight of the coconut,  $d$  is the distance the nut falls,  $m$  is the mass of the coconut,  $v_1$  is the velocity with which it hits the beach, and  $v_2$  is the initial velocity.

## 9.2 Mechanical Energy and Conservation of Energy

### Section Learning Objectives

*By the end of this section, you will be able to do the following:*

- Explain the law of conservation of energy in terms of kinetic and potential energy
- Perform calculations related to kinetic and potential energy. Apply the law of conservation of energy

### Section Key Terms

law of conservation of energy

### Mechanical Energy and Conservation of Energy

We saw earlier that mechanical energy can be either potential or kinetic. In this section we will see how energy is transformed from one of these forms to the other. We will also see that, in a closed system, the sum of these forms of energy remains constant.

Quite a bit of potential energy is gained by a roller coaster car and its passengers when they are raised to the top of the first hill. Remember that the *potential* part of the term means that energy has been stored and can be used at another time. You will see that this stored energy can either be used to do work or can be transformed into kinetic energy. For example, when an object that has gravitational potential energy falls, its energy is converted to kinetic energy. Remember that both work and energy are expressed in joules.

Refer back to . The amount of work required to raise the TV from point A to point B is equal to the amount of gravitational potential energy the TV gains from its height above the ground. This is generally true for any object raised above the ground. If all the work done on an object is used to raise the object above the ground, the amount work equals the object's gain in gravitational potential energy. However, note that because of the work done by friction, these energy–work transformations are never perfect. Friction causes the loss of some useful energy. In the discussions to follow, we will use the approximation that transformations are frictionless.

Now, let's look at the roller coaster in [Figure 9.6](#). Work was done on the roller coaster to get it to the top of the first rise; at this point, the roller coaster has gravitational potential energy. It is moving slowly, so it also has a small amount of kinetic energy. As the car descends the first slope, its *PE* is converted to *KE*. At the low point much of the original *PE* has been transformed to *KE*, and speed is at a maximum. As the car moves up the next slope, some of the *KE* is transformed back into *PE* and the car slows down.



Figure 9.6 During this roller coaster ride, there are conversions between potential and kinetic energy.

## Virtual Physics

### Energy Skate Park Basics

This simulation shows how kinetic and potential energy are related, in a scenario similar to the roller coaster. Observe the changes in *KE* and *PE* by clicking on the bar graph boxes. Also try the three differently shaped skate parks. Drag the skater to the track to start the animation.

[Click to view content \(http://phet.colorado.edu/sims/html/energy-skate-park-basics/latest/energy-skate-park-basics\\_en.html\)](http://phet.colorado.edu/sims/html/energy-skate-park-basics/latest/energy-skate-park-basics_en.html)

### GRASP CHECK

This simulation (<http://phet.colorado.edu/en/simulation/energy-skate-park-basics>) shows how kinetic and potential energy are related, in a scenario similar to the roller coaster. Observe the changes in *KE* and *PE* by clicking on the bar graph boxes. Also try the three differently shaped skate parks. Drag the skater to the track to start the animation. The bar graphs show how *KE* and *PE* are transformed back and forth. Which statement best explains what happens to the mechanical energy of the system as speed is increasing?

- The mechanical energy of the system increases, provided there is no loss of energy due to friction. The energy would transform to kinetic energy when the speed is increasing.
- The mechanical energy of the system remains constant provided there is no loss of energy due to friction. The energy would transform to kinetic energy when the speed is increasing.
- The mechanical energy of the system increases provided there is no loss of energy due to friction. The energy would transform to potential energy when the speed is increasing.
- The mechanical energy of the system remains constant provided there is no loss of energy due to friction. The energy would transform to potential energy when the speed is increasing.

On an actual roller coaster, there are many ups and downs, and each of these is accompanied by transitions between kinetic and potential energy. Assume that no energy is lost to friction. At any point in the ride, the total mechanical energy is the same, and it is equal to the energy the car had at the top of the first rise. This is a result of the **law of conservation of energy**, which says that, in a closed system, total energy is conserved—that is, it is constant. Using subscripts 1 and 2 to represent initial and final energy, this law is expressed as

$$KE_1 + PE_1 = KE_2 + PE_2.$$

Either side equals the total mechanical energy. The phrase *in a closed system* means we are assuming no energy is lost to the surroundings due to friction and air resistance. If we are making calculations on dense falling objects, this is a good assumption. For the roller coaster, this assumption introduces some inaccuracy to the calculation.



## Calculations Involving Mechanical Energy and Conservation of Energy

### TIPS FOR SUCCESS

When calculating work or energy, use units of meters for distance, newtons for force, kilograms for mass, and seconds for time. This will assure that the result is expressed in joules.



### WATCH PHYSICS

#### Conservation of Energy

This video discusses conversion of  $PE$  to  $KE$  and conservation of energy. The scenario is very similar to the roller coaster and the skate park. It is also a good explanation of the energy changes studied in the snap lab.

[Click to view content \(https://www.khanacademy.org/embed\\_video?v=kw\\_4Loo1HR4\)](https://www.khanacademy.org/embed_video?v=kw_4Loo1HR4)

#### GRASP CHECK

Did you expect the speed at the bottom of the slope to be the same as when the object fell straight down? Which statement best explains why this is not exactly the case in real-life situations?

- The speed was the same in the scenario in the animation because the object was sliding on the ice, where there is large amount of friction. In real life, much of the mechanical energy is lost as heat caused by friction.
- The speed was the same in the scenario in the animation because the object was sliding on the ice, where there is small amount of friction. In real life, much of the mechanical energy is lost as heat caused by friction.
- The speed was the same in the scenario in the animation because the object was sliding on the ice, where there is large amount of friction. In real life, no mechanical energy is lost due to conservation of the mechanical energy.
- The speed was the same in the scenario in the animation because the object was sliding on the ice, where there is small amount of friction. In real life, no mechanical energy is lost due to conservation of the mechanical energy.



### WORKED EXAMPLE

#### Applying the Law of Conservation of Energy

A 10 kg rock falls from a 20 m cliff. What is the kinetic and potential energy when the rock has fallen 10 m?

##### Strategy

Choose the equation.

$$KE_1 + PE_1 = KE_2 + PE_2$$

$$KE = \frac{1}{2}mv^2; \quad PE = mgh$$

$$\frac{1}{2}mv_1^2 + mgh_1 = \frac{1}{2}mv_2^2 + mgh_2$$

9.4

9.5

9.6

List the knowns.

$$m = 10 \text{ kg}, \quad v_1 = 0, \quad g = 9.80$$

$$\frac{m}{s^2},$$

9.7

$$h_1 = 20 \text{ m}, \quad h_2 = 10 \text{ m}$$

Identify the unknowns.

$$KE_2 \text{ and } PE_2$$

Substitute the known values into the equation and solve for the unknown variables.

**Solution**

$$PE_2 = mgh_2 = 10(9.80)10 = 980 \text{ J}$$

9.8

$$KE_2 = PE_2 - (KE_1 + PE_1) = 980 - \{[0 - [10(9.80)20]]\} = 980 \text{ J}$$

9.9

**Discussion**

Alternatively, conservation of energy equation could be solved for  $v_2$  and  $KE_2$  could be calculated. Note that  $m$  could also be eliminated.

**TIPS FOR SUCCESS**

Note that we can solve many problems involving conversion between  $KE$  and  $PE$  without knowing the mass of the object in question. This is because kinetic and potential energy are both proportional to the mass of the object. In a situation where  $KE = PE$ , we know that  $mgh = (1/2)mv^2$ .

Dividing both sides by  $m$  and rearranging, we have the relationship

$$2gh = v^2.$$

**Practice Problems**

- A child slides down a playground slide. If the slide is 3 m high and the child weighs 300 N, how much potential energy does the child have at the top of the slide? (Round  $g$  to  $10 \text{ m/s}^2$ .)
  - 0 J
  - 100 J
  - 300 J
  - 900 J
- A 0.2 kg apple on an apple tree has a potential energy of 10 J. It falls to the ground, converting all of its PE to kinetic energy. What is the velocity of the apple just before it hits the ground?
  - 0 m/s
  - 2 m/s
  - 10 m/s
  - 50 m/s

**Snap Lab****Converting Potential Energy to Kinetic Energy**

In this activity, you will calculate the potential energy of an object and predict the object's speed when all that potential energy has been converted to kinetic energy. You will then check your prediction.

You will be dropping objects from a height. Be sure to stay a safe distance from the edge. Don't lean over the railing too far. Make sure that you do not drop objects into an area where people or vehicles pass by. Make sure that dropping objects will not cause damage.

You will need the following:

Materials for each pair of students:

- Four marbles (or similar small, dense objects)
- Stopwatch

Materials for class:

- Metric measuring tape long enough to measure the chosen height
- A scale

Instructions

## Procedure

1. Work with a partner. Find and record the mass of four small, dense objects per group.
2. Choose a location where the objects can be safely dropped from a height of at least 15 meters. A bridge over water with a safe pedestrian walkway will work well.
3. Measure the distance the object will fall.
4. Calculate the potential energy of the object before you drop it using  $PE = mgh = (9.80)mh$ .
5. Predict the kinetic energy and velocity of the object when it lands using  $PE = KE$  and so,  $mgh = \frac{mv^2}{2}$ ;  $v = \sqrt{2(9.80)h} = 4.43\sqrt{h}$ .
6. One partner drops the object while the other measures the time it takes to fall.
7. Take turns being the dropper and the timer until you have made four measurements.
8. Average your drop multiplied by and calculate the velocity of the object when it landed using  $v = at = gt = (9.80)t$ .
9. Compare your results to your prediction.

## GRASP CHECK

Galileo's experiments proved that, contrary to popular belief, heavy objects do not fall faster than light objects. How do the equations you used support this fact?

- a. Heavy objects do not fall faster than the light objects because while conserving the mechanical energy of the system, the mass term gets cancelled and the velocity is independent of the mass. In real life, the variation in the velocity of the different objects is observed because of the non-zero air resistance.
- b. Heavy objects do not fall faster than the light objects because while conserving the mechanical energy of the system, the mass term does not get cancelled and the velocity is dependent on the mass. In real life, the variation in the velocity of the different objects is observed because of the non-zero air resistance.
- c. Heavy objects do not fall faster than the light objects because while conserving the mechanical energy the system, the mass term gets cancelled and the velocity is independent of the mass. In real life, the variation in the velocity of the different objects is observed because of zero air resistance.
- d. Heavy objects do not fall faster than the light objects because while conserving the mechanical energy of the system, the mass term does not get cancelled and the velocity is dependent on the mass. In real life, the variation in the velocity of the different objects is observed because of zero air resistance.

## Check Your Understanding

7. Describe the transformation between forms of mechanical energy that is happening to a falling skydiver before his parachute opens.
  - a. Kinetic energy is being transformed into potential energy.
  - b. Potential energy is being transformed into kinetic energy.
  - c. Work is being transformed into kinetic energy.
  - d. Kinetic energy is being transformed into work.
8. True or false—If a rock is thrown into the air, the increase in the height would increase the rock's kinetic energy, and then the increase in the velocity as it falls to the ground would increase its potential energy.
  - a. True
  - b. False
9. Identify equivalent terms for *stored energy* and *energy of motion*.
  - a. Stored energy is potential energy, and energy of motion is kinetic energy.
  - b. Energy of motion is potential energy, and stored energy is kinetic energy.
  - c. Stored energy is the potential as well as the kinetic energy of the system.
  - d. Energy of motion is the potential as well as the kinetic energy of the system.

## 9.3 Simple Machines

### Section Learning Objectives

*By the end of this section, you will be able to do the following:*

- Describe simple and complex machines
- Calculate mechanical advantage and efficiency of simple and complex machines

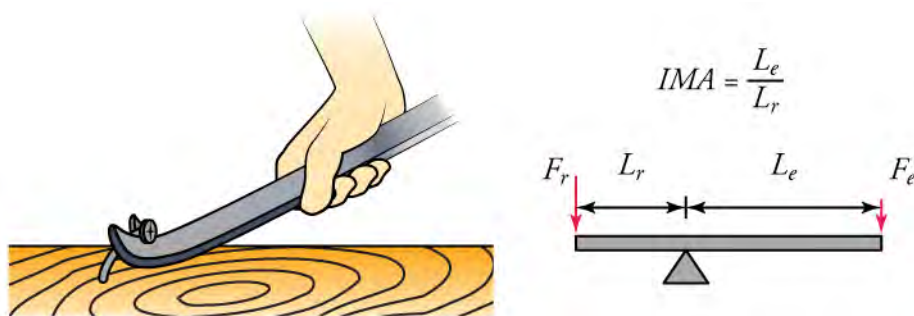
### Section Key Terms

complex machine	efficiency output	ideal mechanical advantage	inclined plane	input work
lever	mechanical advantage	output work	pulley	screw
simple machine	wedge	wheel and axle		

### Simple Machines

**Simple machines** make work easier, but they do not decrease the amount of work you have to do. Why can't simple machines change the amount of work that you do? Recall that in closed systems the total amount of energy is conserved. A machine cannot increase the amount of energy you put into it. So, why is a simple machine useful? Although it cannot change the amount of work you do, a simple machine can change the amount of force you must apply to an object, and the distance over which you apply the force. In most cases, a simple machine is used to reduce the amount of force you must exert to do work. The down side is that you must exert the force over a greater distance, because the product of force and distance,  $fd$ , (which equals work) does not change.

Let's examine how this works in practice. In [Figure 9.7\(a\)](#), the worker uses a type of **lever** to exert a small force over a large distance, while the pry bar pulls up on the nail with a large force over a small distance. [Figure 9.7\(b\)](#) shows how a lever works mathematically. The effort force, applied at  $\mathbf{F}_e$ , lifts the load (the resistance force) which is pushing down at  $\mathbf{F}_r$ . The triangular pivot is called the fulcrum; the part of the lever between the fulcrum and  $\mathbf{F}_e$  is the effort arm,  $L_e$ , and the part to the left is the resistance arm,  $L_r$ . The **mechanical advantage** is a number that tells us how many times a simple machine multiplies the effort force. The **ideal mechanical advantage**,  $IMA$ , is the mechanical advantage of a perfect machine with no loss of useful work caused by friction between moving parts. The equation for  $IMA$  is shown in [Figure 9.7\(b\)](#).



**Figure 9.7** (a) A pry bar is a type of lever. (b) The ideal mechanical advantage equals the length of the effort arm divided by the length of the resistance arm of a lever.

In general, the  $IMA$  = the resistance force,  $\mathbf{F}_r$ , divided by the effort force,  $\mathbf{F}_e$ .  $IMA$  also equals the distance over which the effort is applied,  $d_e$ , divided by the distance the load travels,  $d_r$ .

$$IMA = \frac{\mathbf{F}_r}{\mathbf{F}_e} = \frac{d_e}{d_r}$$

Getting back to conservation of energy, for any simple machine, the work put into the machine,  $W_i$ , equals the work the machine puts out,  $W_o$ . Combining this with the information in the paragraphs above, we can write

$$W_i = W_o$$

$$\mathbf{F}_e d_e = \mathbf{F}_r d_r$$

$$\text{If } \mathbf{F}_e < \mathbf{F}_r, \text{ then } d_e > d_r.$$

The equations show how a simple machine can output the same amount of work while reducing the amount of effort force by increasing the distance over which the effort force is applied.



## WATCH PHYSICS

### Introduction to Mechanical Advantage

This video shows how to calculate the *IMA* of a lever by three different methods: (1) from effort force and resistance force; (2) from the lengths of the lever arms, and; (3) from the distance over which the force is applied and the distance the load moves.

[Click to view content \(https://www.youtube.com/embed/pfzJ-z5Ij48\)](https://www.youtube.com/embed/pfzJ-z5Ij48)

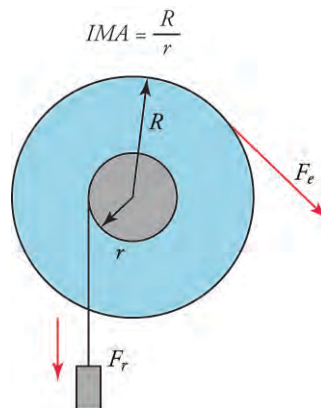
#### GRASP CHECK

Two children of different weights are riding a seesaw. How do they position themselves with respect to the pivot point (the fulcrum) so that they are balanced?

- The heavier child sits closer to the fulcrum.
- The heavier child sits farther from the fulcrum.
- Both children sit at equal distance from the fulcrum.
- Since both have different weights, they will never be in balance.

Some levers exert a large force to a short effort arm. This results in a smaller force acting over a greater distance at the end of the resistance arm. Examples of this type of lever are baseball bats, hammers, and golf clubs. In another type of lever, the fulcrum is at the end of the lever and the load is in the middle, as in the design of a wheelbarrow.

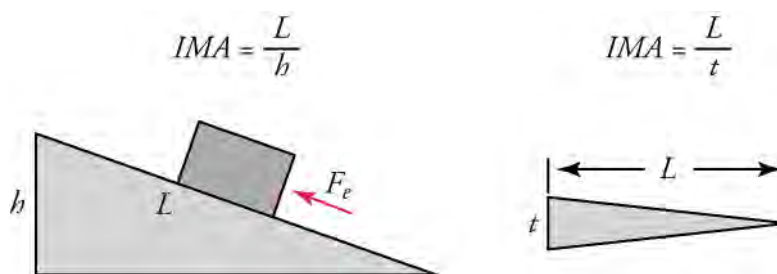
The simple machine shown in [Figure 9.8](#) is called a **wheel and axle**. It is actually a form of lever. The difference is that the effort arm can rotate in a complete circle around the fulcrum, which is the center of the axle. Force applied to the outside of the wheel causes a greater force to be applied to the rope that is wrapped around the axle. As shown in the figure, the ideal mechanical advantage is calculated by dividing the radius of the wheel by the radius of the axle. Any crank-operated device is an example of a wheel and axle.



**Figure 9.8** Force applied to a wheel exerts a force on its axle.

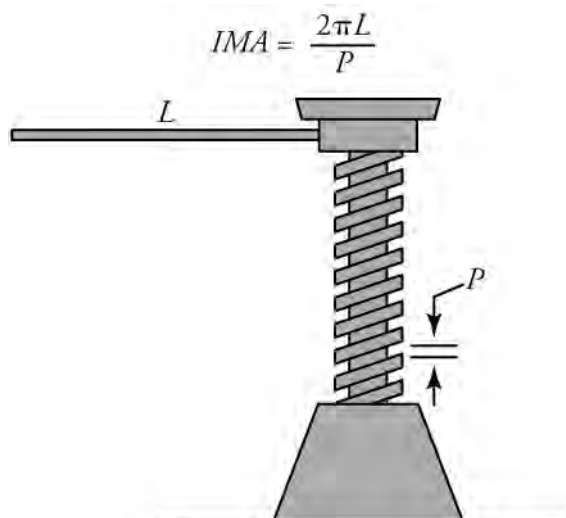
An **inclined plane** and a **wedge** are two forms of the same simple machine. A wedge is simply two inclined planes back to back. [Figure 9.9](#) shows the simple formulas for calculating the *IMAs* of these machines. All sloping, paved surfaces for walking or driving are inclined planes. Knives and axe heads are examples of wedges.





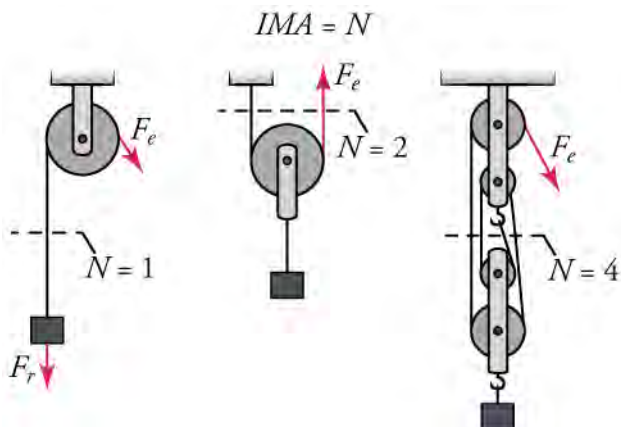
**Figure 9.9** An inclined plane is shown on the left, and a wedge is shown on the right.

The **screw** shown in [Figure 9.10](#) is actually a lever attached to a circular inclined plane. Wood screws (of course) are also examples of screws. The lever part of these screws is a screw driver. In the formula for *IMA*, the distance between screw threads is called *pitch* and has the symbol *P*.



**Figure 9.10** The screw shown here is used to lift very heavy objects, like the corner of a car or a house a short distance.

[Figure 9.11](#) shows three different **pulley** systems. Of all simple machines, mechanical advantage is easiest to calculate for pulleys. Simply count the number of ropes supporting the load. That is the *IMA*. Once again we have to exert force over a longer distance to multiply force. To raise a load 1 meter with a pulley system you have to pull *N* meters of rope. Pulley systems are often used to raise flags and window blinds and are part of the mechanism of construction cranes.



**Figure 9.11** Three pulley systems are shown here.



## WATCH PHYSICS

### Mechanical Advantage of Inclined Planes and Pulleys

The first part of this video shows how to calculate the *IMA* of pulley systems. The last part shows how to calculate the *IMA* of an inclined plane.

[Click to view content \(https://www.khanacademy.org/embed\\_video?v=vSsK7Rfa3yA\)](https://www.khanacademy.org/embed_video?v=vSsK7Rfa3yA)

#### GRASP CHECK

How could you use a pulley system to lift a light load to great height?

- Reduce the radius of the pulley.
- Increase the number of pulleys.
- Decrease the number of ropes supporting the load.
- Increase the number of ropes supporting the load.

A **complex machine** is a combination of two or more simple machines. The wire cutters in [Figure 9.12](#) combine two levers and two wedges. Bicycles include wheel and axles, levers, screws, and pulleys. Cars and other vehicles are combinations of many machines.



Figure 9.12 Wire cutters are a common complex machine.

## Calculating Mechanical Advantage and Efficiency of Simple Machines

In general, the *IMA* = the resistance force,  $F_r$ , divided by the effort force,  $F_e$ . *IMA* also equals the distance over which the effort is applied,  $d_e$ , divided by the distance the load travels,  $d_r$ .

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

Refer back to the discussions of each simple machine for the specific equations for the *IMA* for each type of machine.

No simple or complex machines have the actual mechanical advantages calculated by the *IMA* equations. In real life, some of the applied work always ends up as wasted heat due to friction between moving parts. Both the **input work** ( $W_i$ ) and **output work** ( $W_o$ ) are the result of a force,  $F$ , acting over a distance,  $d$ .

$$W_i = F_i d_i \text{ and } W_o = F_o d_o$$

The **efficiency output** of a machine is simply the output work divided by the input work, and is usually multiplied by 100 so that it is expressed as a percent.

$$\% \text{ efficiency} = \frac{W_o}{W_i} \times 100$$

Look back at the pictures of the simple machines and think about which would have the highest efficiency. Efficiency is related to friction, and friction depends on the smoothness of surfaces and on the area of the surfaces in contact. How would lubrication affect the efficiency of a simple machine?



## WORKED EXAMPLE

### Efficiency of a Lever

The input force of 11 N acting on the effort arm of a lever moves 0.4 m, which lifts a 40 N weight resting on the resistance arm a

distance of 0.1 m. What is the efficiency of the machine?

**Strategy**

State the equation for efficiency of a simple machine,  $\% \text{ efficiency} = \frac{W_o}{W_i} \times 100$ , and calculate  $W_o$  and  $W_i$ . Both work values are the product  $Fd$ .

**Solution**

$W_i = \mathbf{F}_i d_i = (11)(0.4) = 4.4 \text{ J}$  and  $W_o = \mathbf{F}_o d_o = (40)(0.1) = 4.0 \text{ J}$ , then  $\% \text{ efficiency} = \frac{W_o}{W_i} \times 100 = \frac{4.0}{4.4} \times 100 = 91\%$

**Discussion**

Efficiency in real machines will always be less than 100 percent because of work that is converted to unavailable heat by friction and air resistance.  $W_o$  and  $W_i$  can always be calculated as a force multiplied by a distance, although these quantities are not always as obvious as they are in the case of a lever.

---

## Practice Problems

10. What is the IMA of an inclined plane that is 5 m long and 2 m high?
  - a. 0.4
  - b. 2.5
  - c. 0.4 m
  - d. 2.5 m
11. If a pulley system can lift a 200N load with an effort force of 52 N and has an efficiency of almost 100 percent, how many ropes are supporting the load?
  - a. 1 rope is required because the actual mechanical advantage is 0.26.
  - b. 1 rope is required because the actual mechanical advantage is 3.80.
  - c. 4 ropes are required because the actual mechanical advantage is 0.26.
  - d. 4 ropes are required because the actual mechanical advantage is 3.80.

## Check Your Understanding

12. True or false—The efficiency of a simple machine is always less than 100 percent because some small fraction of the input work is always converted to heat energy due to friction.
  - a. True
  - b. False
13. The circular handle of a faucet is attached to a rod that opens and closes a valve when the handle is turned. If the rod has a diameter of 1 cm and the IMA of the machine is 6, what is the radius of the handle?
  - A. 0.08 cm
  - B. 0.17 cm
  - C. 3.0 cm
  - D. 6.0 cm

## KEY TERMS

**complex machine** a machine that combines two or more simple machines

**efficiency** output work divided by input work

**energy** the ability to do work

**gravitational potential energy** energy acquired by doing work against gravity

**ideal mechanical advantage** the mechanical advantage of an idealized machine that loses no energy to friction

**inclined plane** a simple machine consisting of a slope

**input work** effort force multiplied by the distance over which it is applied

**joule** the metric unit for work and energy; equal to 1 newton meter (N•m)

**kinetic energy** energy of motion

**law of conservation of energy** states that energy is neither created nor destroyed

**lever** a simple machine consisting of a rigid arm that pivots on a fulcrum

**mechanical advantage** the number of times the input force is multiplied

**mechanical energy** kinetic or potential energy

**output work** output force multiplied by the distance over which it acts

**potential energy** stored energy

**power** the rate at which work is done

**pulley** a simple machine consisting of a rope that passes over one or more grooved wheels

**screw** a simple machine consisting of a spiral inclined plane

**simple machine** a machine that makes work easier by changing the amount or direction of force required to move an object

**watt** the metric unit of power; equivalent to joules per second

**wedge** a simple machine consisting of two back-to-back inclined planes

**wheel and axle** a simple machine consisting of a rod fixed to the center of a wheel

**work** force multiplied by distance

**work–energy theorem** states that the net work done on a system equals the change in kinetic energy

## SECTION SUMMARY

### 9.1 Work, Power, and the Work–Energy Theorem

- Doing work on a system or object changes its energy.
- The work–energy theorem states that an amount of work that changes the velocity of an object is equal to the change in kinetic energy of that object. The work–energy theorem states that an amount of work that changes the velocity of an object is equal to the change in kinetic energy of that object.
- Power is the rate at which work is done.

### 9.2 Mechanical Energy and Conservation of Energy

- Mechanical energy may be either kinetic (energy of

motion) or potential (stored energy).

- Doing work on an object or system changes its energy.
- Total energy in a closed, isolated system is constant.

### 9.3 Simple Machines

- The six types of simple machines make work easier by changing the  $fd$  term so that force is reduced at the expense of increased distance.
- The ratio of output force to input force is a machine's mechanical advantage.
- Combinations of two or more simple machines are called complex machines.
- The ratio of output work to input work is a machine's efficiency.

## KEY EQUATIONS

### 9.1 Work, Power, and the Work–Energy Theorem

equation for work  $W = \mathbf{f}d$

force  $\mathbf{f} = w = mg$

work equivalencies  $W = PE_e = \mathbf{f}mg$

kinetic energy  $KE = \frac{1}{2}m\mathbf{v}^2$

work–energy theorem  $W = \Delta KE = \frac{1}{2}m\mathbf{v}_2^2 - \frac{1}{2}m\mathbf{v}_1^2$

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

## 9.2 Mechanical Energy and Conservation of Energy

conservation of energy  $KE_1 + PE_1 = KE_2 + PE_2$

## 9.3 Simple Machines

ideal mechanical advantage (general)  $IMA = \frac{F_e}{F_r} = \frac{d_e}{d_r}$

ideal mechanical advantage (lever)  $IMA = \frac{L_o}{L_r}$

ideal mechanical advantage (wheel and axle)  $IMA = \frac{R}{r}$

ideal mechanical advantage (inclined plane)  $IMA = \frac{L}{h}$

ideal mechanical advantage (wedge)  $IMA = \frac{L}{t}$

ideal mechanical advantage (pulley)  $IMA = N$

ideal mechanical advantage (screw)  $IMA = \frac{2\pi L}{P}$

input work  $W_i = F_i d_i$

output work  $W_o = F_o d_o$

efficiency output  $\% \text{ efficiency} = \frac{W_o}{W_i} \times 100$

## CHAPTER REVIEW

### Concept Items

#### 9.1 Work, Power, and the Work–Energy Theorem

- Is it possible for the sum of kinetic energy and potential energy of an object to change without work having been done on the object? Explain.
  - No, because the work-energy theorem states that work done on an object is equal to the change in kinetic energy, and change in KE requires a change in velocity. It is assumed that mass is constant.
  - No, because the work-energy theorem states that work done on an object is equal to the sum of kinetic energy, and the change in KE requires a change in displacement. It is assumed that mass is constant.
  - Yes, because the work-energy theorem states that work done on an object is equal to the change in kinetic energy, and change in KE requires a change in velocity. It is assumed that mass is constant.
  - Yes, because the work-energy theorem states that work done on an object is equal to the sum of kinetic energy, and the change in KE requires a change in displacement. It is assumed that mass is constant.
- Define work for one-dimensional motion.
  - Work is defined as the ratio of the force over the distance.
  - Work is defined as the sum of the force and the distance.
  - Work is defined as the square of the force over the distance.
  - Work is defined as the product of the force and the distance.
- A book with a mass of 0.30 kg falls 2 m from a shelf to the floor. This event is described by the work–energy theorem:  $W = fd = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2$ . Explain why this is enough information to calculate the speed with which the book hits the floor.
  - The mass of the book,  $m$ , and distance,  $d$ , are stated.  $F$  is the weight of the book  $mg$ .  $v_1$  is the initial velocity and  $v_2$  is the final velocity. The final velocity is the only unknown quantity.
  - The mass of the book,  $m$ , and distance,  $d$ , are stated.  $F$  is the weight of the book  $mg$ .  $v_1$  is the final velocity and  $v_2$  is the initial velocity. The final velocity is the only unknown quantity.
  - The mass of the book,  $m$ , and distance,  $d$ , are stated.  $F$  is the weight of the book  $mg$ .  $v_1$  is the initial velocity and  $v_2$  is the final velocity. The final velocity and the initial velocities are the only unknown quantities.
  - The mass of the book,  $m$ , and distance,  $d$ , are stated.  $F$  is the weight of the book  $mg$ .  $v_1$  is the final velocity and  $v_2$  is the initial velocity. The final velocity and the initial velocities are the only unknown quantities.



## 9.2 Mechanical Energy and Conservation of Energy

4. Describe the changes in KE and PE of a person jumping up and down on a trampoline.
  - a. While going up, the person's KE would change to PE. While coming down, the person's PE would change to KE.
  - b. While going up, the person's PE would change to KE. While coming down, the person's KE would change to PE.
  - c. While going up, the person's KE would not change, but while coming down, the person's PE would change to KE.
  - d. While going up, the person's PE would change to KE, but while coming down, the person's KE would not change.
5. You know the height from which an object is dropped. Which equation could you use to calculate the velocity as the object hits the ground?
  - a.  $v = h$
  - b.  $v = \sqrt{2h}$
  - c.  $v = gh$
  - d.  $v = \sqrt{2gh}$
6. The starting line of a cross country foot race is at the bottom of a hill. Which form(s) of mechanical energy of the runners will change when the starting gun is fired?
  - a. Kinetic energy only
  - b. Potential energy only
  - c. Both kinetic and potential energy
  - d. Neither kinetic nor potential energy

## 9.3 Simple Machines

7. How does a simple machine make work easier?
  - a. It reduces the input force and the output force.
  - b. It reduces the input force and increases the output force.
  - c. It increases the input force and reduces the output force.
  - d. It increases the input force and the output force.
8. Which type of simple machine is a knife?
  - a. A ramp
  - b. A wedge
  - c. A pulley
  - d. A screw

## Critical Thinking Items

### 9.1 Work, Power, and the Work-Energy Theorem

9. Which activity requires a person to exert force on an object that causes the object to move but does not change the kinetic or potential energy of the object?
  - a. Moving an object to a greater height with acceleration
  - b. Moving an object to a greater height without acceleration
  - c. Carrying an object with acceleration at the same height
  - d. Carrying an object without acceleration at the same height
10. Which statement explains how it is possible to carry books to school without changing the kinetic or potential energy of the books or doing any work?
  - a. By moving the book without acceleration and keeping the height of the book constant
  - b. By moving the book with acceleration and keeping the height of the book constant
  - c. By moving the book without acceleration and changing the height of the book
  - d. By moving the book with acceleration and changing the height of the book

## 9.2 Mechanical Energy and Conservation of Energy

11. True or false—A cyclist coasts down one hill and up another hill until she comes to a stop. The point at which the bicycle stops is lower than the point at which it started coasting because part of the original potential energy has been converted to a quantity of heat and this makes the tires of the bicycle warm.
  - a. True
  - b. False

## 9.3 Simple Machines

12. We think of levers being used to decrease effort force. Which of the following describes a lever that requires a large effort force which causes a smaller force to act over a large distance and explains how it works?
  - a. Anything that is swung by a handle, such as a hammer or racket. Force is applied near the fulcrum over a short distance, which makes the other end move rapidly over a long distance.
  - b. Anything that is swung by a handle, such as a hammer or racket. Force is applied far from the fulcrum over a large distance, which makes the other end move rapidly over a long distance.
  - c. A lever used to lift a heavy stone. Force is applied near the fulcrum over a short distance, which

- makes the other end lift a heavy object easily.
- d. A lever used to lift a heavy stone. Force is applied far from the fulcrum over a large distance, which makes the other end lift a heavy object easily
13. A baseball bat is a lever. Which of the following explains how a baseball bat differs from a lever like a pry bar?
- In a baseball bat, effort force is smaller and is applied over a large distance, while the resistance force is smaller and is applied over a long distance.

- In a baseball bat, effort force is smaller and is applied over a large distance, while the resistance force is smaller and is applied over a short distance.
- In a baseball bat, effort force is larger and is applied over a short distance, while the resistance force is smaller and is applied over a long distance.
- In a baseball bat, effort force is larger and is applied over a short distance, while the resistance force is smaller and is applied over a short distance.

## Problems

### 9.1 Work, Power, and the Work–Energy Theorem

14. A baseball player exerts a force of 100 N on a ball for a distance of 0.5 m as he throws it. If the ball has a mass of 0.15 kg, what is its velocity as it leaves his hand?
- −36.5 m/s
  - −25.8 m/s
  - 25.8 m/s
  - 36.5 m/s
15. A boy pushes his little sister on a sled. The sled accelerates from 0 to 3.2 m/s. If the combined mass of his sister and the sled is 40.0 kg and 18 W of power were generated, how long did the boy push the sled?
- 205 s
  - 128 s
  - 23 s
  - 11 s

$U = \frac{1}{2}kx^2$ , where  $k$  is the force constant and  $x$  is the distance the spring is compressed from the equilibrium position. Four experimental setups described below can be used to determine the force constant of a spring. Which one(s) require measurement of the fewest number of variables to determine  $k$ ? Assume the acceleration due to gravity is known.

- An object is propelled vertically by a compressed spring.
  - An object is propelled horizontally on a frictionless surface by a compressed spring.
  - An object is statically suspended from a spring.
  - An object suspended from a spring is set into oscillatory motion.
- I only
  - III only
  - I and II only
  - III and IV only

### 9.2 Mechanical Energy and Conservation of Energy

16. What is the kinetic energy of a 0.01 kg bullet traveling at a velocity of 700 m/s?
- 3.5 J
  - 7 J
  - $2.45 \times 10^3$  J
  - $2.45 \times 10^5$  J
17. A marble rolling across a flat, hard surface at 2 m/s rolls up a ramp. Assuming that  $g = 10 \text{ m/s}^2$  and no energy is lost to friction, what will be the vertical height of the marble when it comes to a stop before rolling back down? Ignore effects due to the rotational kinetic energy.
- 0.1 m
  - 0.2 m
  - 0.4 m
  - 2 m

18. The potential energy stored in a compressed spring is

### 9.3 Simple Machines

19. A man is using a wedge to split a block of wood by hitting the wedge with a hammer. This drives the wedge into the wood creating a crack in the wood. When he hits the wedge with a force of 400 N it travels 4 cm into the wood. This caused the wedge to exert a force of 1,400 N sideways increasing the width of the crack by 1 cm. What is the efficiency of the wedge?
- 0.875 percent
  - 0.14
  - 0.751
  - 87.5 percent
20. An electrician grips the handles of a wire cutter, like the one shown, 10 cm from the pivot and places a wire between the jaws 2 cm from the pivot. If the cutter blades are 2 cm wide and 0.3 cm thick, what is the overall IMA of this complex machine?



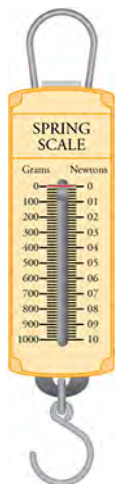
- a. 1.34
- b. 1.53
- c. 33.3
- d. 33.5

## Performance Task

### 9.3 Simple Machines

21. Conservation of Energy and Energy Transfer; Cause and Effect; and S&EP, Planning and Carrying Out Investigations

Plan an investigation to measure the mechanical advantage of simple machines and compare to the *IMA* of the machine. Also measure the efficiency of each machine studied. Design an investigation to make these measurements for these simple machines: lever, inclined plane, wheel and axle and a pulley system. In addition to these machines, include a spring scale, a tape measure, and a weight with a loop on top that can be attached to the hook on the spring scale. A spring scale is shown in the image.



A spring scale measures weight, not mass.

**LEVER:** Beginning with the lever, explain how you would measure input force, output force, effort arm, and resistance arm. Also explain how you would find the distance the load travels and the distance over which the effort force is applied. Explain how you would use this data to determine *IMA* and efficiency.

**INCLINED PLANE:** Make measurements to determine *IMA* and efficiency of an inclined plane. Explain how you would use the data to calculate these values. Which property do you already know? Note that there are no effort and resistance arm measurements, but there are height and length measurements.

**WHEEL AND AXLE:** Again, you will need two force measurements and four distance measurements. Explain how you would use these to calculate *IMA* and efficiency.

**SCREW:** You will need two force measurements, two distance traveled measurements, and two length measurements. You may describe a screw like the one shown in [Figure 9.10](#) or you could use a screw and screw driver. (Measurements would be easier for the former). Explain how you would use these to calculate *IMA* and efficiency.

**PULLEY SYSTEM:** Explain how you would determine the *IMA* and efficiency of the four-pulley system shown in [Figure 9.11](#). Why do you only need two distance measurements for this machine?

Design a table that compares the efficiency of the five simple machines. Make predictions as to the most and least efficient machines.

## TEST PREP

### Multiple Choice

#### 9.1 Work, Power, and the Work–Energy Theorem

22. Which expression represents power?

- a.  $fd$
- b.  $mgh$
- c.  $\frac{mv^2}{2}$
- d.  $\frac{W}{t}$

23. The work–energy theorem states that the change in the kinetic energy of an object is equal to what?

- a. The work done on the object
- b. The force applied to the object
- c. The loss of the object's potential energy
- d. The object's total mechanical energy minus its kinetic energy

24. A runner at the start of a race generates 250 W of power as he accelerates to 5 m/s. If the runner has a mass of 60 kg, how long did it take him to reach that speed?

- a. 0.33 s
- b. 0.83 s
- c. 1.2 s
- d. 3.0 s

25. A car's engine generates 100,000 W of power as it exerts a force of 10,000 N. How long does it take the car to travel 100 m?
- 0.001 s
  - 0.01 s
  - 10 s
  - 1,000 s

## 9.2 Mechanical Energy and Conservation of Energy

26. Why is this expression for kinetic energy incorrect?  
 $KE = (m)(v)^2$ .
- The constant  $g$  is missing.
  - The term  $v$  should not be squared.
  - The expression should be divided by 2.
  - The energy lost to friction has not been subtracted.
27. What is the kinetic energy of a 10 kg object moving at 2.0 m/s?
- 10 J
  - 20 J
  - 40 J
  - 100 J
28. Which statement best describes the PE-KE transformations for a javelin, starting from the instant the javelin leaves the thrower's hand until it hits the ground.
- Initial PE is transformed to KE until the javelin reaches the high point of its arc. On the way back down, KE is transformed into PE. At every point in the flight, mechanical energy is being transformed into heat energy.
  - Initial KE is transformed to PE until the javelin reaches the high point of its arc. On the way back down, PE is transformed into KE. At every point in the flight, mechanical energy is being transformed into heat energy.
  - Initial PE is transformed to KE until the javelin reaches the high point of its arc. On the way back down, there is no transformation of mechanical energy. At every point in the flight, mechanical energy is being transformed into heat energy.
  - Initial KE is transformed to PE until the javelin reaches the high point of its arc. On the way back down, there is no transformation of mechanical energy. At every point in the flight, mechanical energy is being transformed into heat energy.
29. At the beginning of a roller coaster ride, the roller coaster car has an initial energy mostly in the form of PE. Which statement explains why the fastest speeds of the car will be at the lowest points in the ride?
- At the bottom of the slope kinetic energy is at its

maximum value and potential energy is at its minimum value.

- At the bottom of the slope potential energy is at its maximum value and kinetic energy is at its minimum value.
- At the bottom of the slope both kinetic and potential energy reach their maximum values
- At the bottom of the slope both kinetic and potential energy reach their minimum values.

## 9.3 Simple Machines

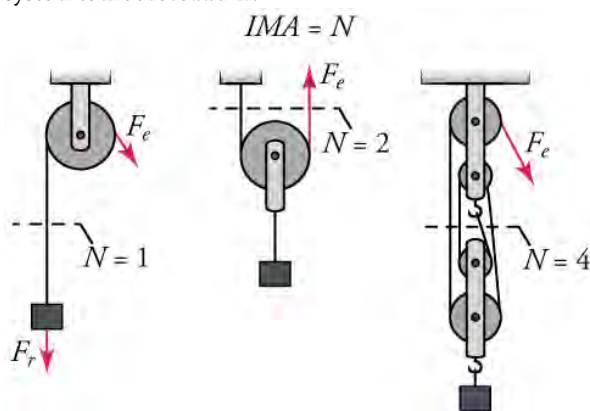
30. A large radius divided by a small radius is the expression used to calculate the IMA of what?
- A screw
  - A pulley
  - A wheel and axle
  - An inclined plane.
31. What is the IMA of a wedge that is 12 cm long and 3 cm thick?
- 2
  - 3
  - 4
  - 9
32. Which statement correctly describes the simple machines, like the crank in the image, that make up an Archimedes screw and the forces it applies?



- The crank is a wedge in which the IMA is the length of the tube divided by the radius of the tube. The applied force is the effort force and the weight of the water is the resistance force.
  - The crank is an inclined plane in which the IMA is the length of the tube divided by the radius of the tube. The applied force is the effort force and the weight of the water is the resistance force.
  - The crank is a wheel and axle. The effort force of the crank becomes the resistance force of the screw.
  - The crank is a wheel and axle. The resistance force of the crank becomes the effort force of the screw.
33. Refer to the pulley system on right in the image. Assume this pulley system is an ideal machine. How hard would you have to pull on the rope to lift a 120 N

load?

How many meters of rope would you have to pull out of the system to lift the load 1 m?



- a. 480 N  
4 m
- b. 480 N  
 $\frac{1}{4}$  m
- c. 30 N  
4 m
- d. 30 N  
 $\frac{1}{4}$  m

## Short Answer

### 9.1 Work, Power, and the Work-Energy Theorem

34. Describe two ways in which doing work on an object can increase its mechanical energy.
  - a. Raising an object to a higher elevation does work as it increases its PE; increasing the speed of an object does work as it increases its KE.
  - b. Raising an object to a higher elevation does work as it increases its KE; increasing the speed of an object does work as it increases its PE.
  - c. Raising an object to a higher elevation does work as it increases its PE; decreasing the speed of an object does work as it increases its KE.
  - d. Raising an object to a higher elevation does work as it increases its KE; decreasing the speed of an object does work as it increases its PE.
35. True or false—While riding a bicycle up a gentle hill, it is fairly easy to increase your potential energy, but to increase your kinetic energy would make you feel exhausted.
  - a. True
  - b. False
36. Which statement best explains why running on a track with constant speed at 3 m/s is not work, but climbing a mountain at 1 m/s is work?
  - a. At constant speed, change in the kinetic energy is zero but climbing a mountain produces change in the potential energy.
  - b. At constant speed, change in the potential energy is zero, but climbing a mountain produces change in the kinetic energy.
  - c. At constant speed, change in the kinetic energy is finite, but climbing a mountain produces no

change in the potential energy.

- d. At constant speed, change in the potential energy is finite, but climbing a mountain produces no change in the kinetic energy.
37. You start at the top of a hill on a bicycle and coast to the bottom without applying the brakes. By the time you reach the bottom of the hill, work has been done on you and your bicycle, according to the equation:  $W = \frac{1}{2}m(v_2^2 - v_1^2)$ . If  $m$  is the mass of you and your bike, what are  $v_1$  and  $v_2$ ?
    - a.  $v_1$  is your speed at the top of the hill, and  $v_2$  is your speed at the bottom.
    - b.  $v_1$  is your speed at the bottom of the hill, and  $v_2$  is your speed at the top.
    - c.  $v_1$  is your displacement at the top of the hill, and  $v_2$  is your displacement at the bottom.
    - d.  $v_1$  is your displacement at the bottom of the hill, and  $v_2$  is your displacement at the top.

### 9.2 Mechanical Energy and Conservation of Energy

38. True or false—The formula for gravitational potential energy can be used to explain why joules, J, are equivalent to  $\text{kg} \times \text{m}^2 / \text{s}^2$ . Show your work.
  - a. True
  - b. False
39. Which statement best explains why accelerating a car from 20 mph to 40 mph quadruples its kinetic energy?
  - a. Because kinetic energy is directly proportional to the square of the velocity.
  - b. Because kinetic energy is inversely proportional to the square of the velocity.
  - c. Because kinetic energy is directly proportional to the fourth power of the velocity.
  - d. Because kinetic energy is inversely proportional to



the fourth power of the velocity.

40. A coin falling through a vacuum loses no energy to friction, and yet, after it hits the ground, it has lost all its potential and kinetic energy. Which statement best explains why the law of conservation of energy is still valid in this case?

- When the coin hits the ground, the ground gains potential energy that quickly changes to thermal energy.
- When the coin hits the ground, the ground gains kinetic energy that quickly changes to thermal energy.
- When the coin hits the ground, the ground gains thermal energy that quickly changes to kinetic energy.
- When the coin hits the ground, the ground gains thermal energy that quickly changes to potential energy.

41. True or false—A marble rolls down a slope from height  $h_1$  and up another slope to height  $h_2$ , where ( $h_2 < h_1$ ). The difference  $mg(h_1 - h_2)$  is equal to the heat lost due to the friction.

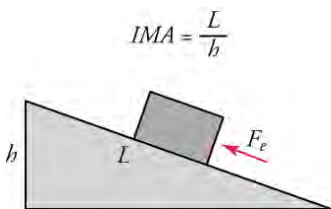
- True
- False

### 9.3 Simple Machines

42. Why would you expect the lever shown in the top image to have a greater efficiency than the inclined plane shown in the bottom image?



$$IMA = \frac{L_e}{L_r}$$



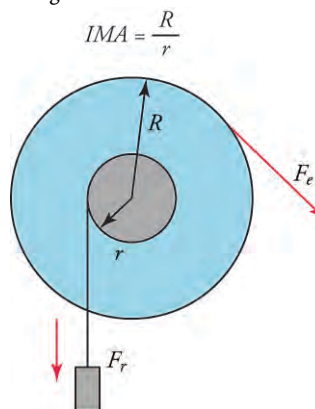
$$IMA = \frac{L}{t}$$

- The resistance arm is shorter in case of the inclined

plane.

- The effort arm is shorter in case of the inclined plane.
- The area of contact is greater in case of the inclined plane.

43. Why is the wheel on a wheelbarrow **not** a simple machine in the same sense as the simple machine in the image?



- The wheel on the wheelbarrow has no fulcrum.
- The center of the axle is not the fulcrum for the wheels of a wheelbarrow.
- The wheelbarrow differs in the way in which load is attached to the axle.
- The wheelbarrow has less resistance force than a wheel and axle design.

44. A worker pulls down on one end of the rope of a pulley system with a force of 75 N to raise a hay bale tied to the other end of the rope. If she pulls the rope down 2.0 m and the bale raises 1.0 m, what else would you have to know to calculate the efficiency of the pulley system?

- the weight of the worker
- the weight of the hay bale
- the radius of the pulley
- the height of the pulley from ground

45. True or false—A boy pushed a box with a weight of 300 N up a ramp. He said that, because the ramp was 1.0 m high and 3.0 m long, he must have been pushing with force of exactly 100 N.

- True
- False

## Extended Response

### 9.1 Work, Power, and the Work-Energy Theorem

46. Work can be negative as well as positive because an object or system can do work on its surroundings as well as have work done on it. Which of the following

statements describes:

a situation in which an object does work on its surroundings by decreasing its velocity and a situation in which an object can do work on its surroundings by decreasing its altitude?

- A gasoline engine burns less fuel at a slower speed. Solar cells capture sunlight to generate electricity.

- b. A hybrid car charges its batteries as it decelerates.  
Falling water turns a turbine to generate electricity.
- c. Airplane flaps use air resistance to slow down for landing.  
Rising steam turns a turbine to generate electricity.
- d. An electric train requires less electrical energy as it decelerates.  
A parachute captures air to slow a skydiver's fall.
47. A boy is pulling a girl in a child's wagon at a constant speed. He begins to pull harder, which increases the speed of the wagon. Which of the following describes two ways you could calculate the change in energy of the wagon and girl if you had all the information you needed?
- Calculate work done from the force and the velocity.  
Calculate work done from the change in the potential energy of the system.
  - Calculate work done from the force and the displacement.  
Calculate work done from the change in the potential energy of the system.
  - Calculate work done from the force and the velocity.  
Calculate work done from the change in the kinetic energy of the system.
  - Calculate work done from the force and the displacement.  
Calculate work done from the change in the kinetic energy of the system.
48. Acceleration due to gravity on the moon is  $1.6 \text{ m/s}^2$  or about 16% of the value of  $g$  on Earth.  
If an astronaut on the moon threw a moon rock to a height of 7.8 m, what would be its velocity as it struck the moon's surface?  
How would the fact that the moon has no atmosphere affect the velocity of the falling moon rock? Explain your answer.
- The velocity of the rock as it hits the ground would be 5.0 m/s. Due to the lack of air friction, there would be complete transformation of the potential energy into the kinetic energy as the rock hits the moon's surface.
  - The velocity of the rock as it hits the ground would be 5.0 m/s. Due to the lack of air friction, there would be incomplete transformation of the potential energy into the kinetic energy as the rock hits the moon's surface.
  - The velocity of the rock as it hits the ground would be 12 m/s. Due to the lack of air friction, there would be complete transformation of the potential energy into the kinetic energy as the rock hits the moon's surface.
  - The velocity of the rock as it hits the ground would be 12 m/s. Due to the lack of air friction, there would be incomplete transformation of the potential energy into the kinetic energy as the rock hits the moon's surface.
49. A boulder rolls from the top of a mountain, travels across a valley below, and rolls part way up the ridge on the opposite side. Describe all the energy transformations taking place during these events and identify when they happen.
- As the boulder rolls down the mountainside, KE is converted to PE. As the boulder rolls up the opposite slope, PE is converted to KE. The boulder rolls only partway up the ridge because some of the PE has been converted to thermal energy due to friction.
  - As the boulder rolls down the mountainside, KE is converted to PE. As the boulder rolls up the opposite slope, KE is converted to PE. The boulder rolls only partway up the ridge because some of the PE has been converted to thermal energy due to friction.
  - As the boulder rolls down the mountainside, PE is converted to KE. As the boulder rolls up the opposite slope, PE is converted to KE. The boulder rolls only partway up the ridge because some of the PE has been converted to thermal energy due to friction.
  - As the boulder rolls down the mountainside, PE is converted to KE. As the boulder rolls up the opposite slope, KE is converted to PE. The boulder rolls only partway up the ridge because some of the PE has been converted to thermal energy due to friction.

## 9.2 Mechanical Energy and Conservation of Energy

## 9.3 Simple Machines

50. To dig a hole, one holds the handles together and thrusts the blades of a posthole digger, like the one in the image, into the ground. Next, the handles are pulled apart, which squeezes the dirt between them, making it possible to remove the dirt from the hole. This complex machine is composed of two pairs of two different simple machines. Identify and describe the parts that are simple machines and explain how you would find the IMA of each type of simple machine.



- Each handle and its attached blade is a lever with the

- fulcrum at the hinge. Each blade is a wedge.  
The IMA of a lever would be the length of the handle divided by the length of the blade. The IMA of the wedges would be the length of the blade divided by its width.
- b. Each handle and its attached blade is a lever with the fulcrum at the end. Each blade is a wedge.  
The IMA of a lever would be the length of the handle divided by the length of the blade. The IMA of the wedges would be the length of the blade divided by its width.
- c. Each handle and its attached blade is a lever with the fulcrum at the hinge. Each blade is a wedge.  
The IMA of a lever would be the length of the handle multiplied by the length of the blade. The IMA of the wedges would be the length of the blade multiplied by its width.
- d. Each handle and its attached blade is a lever with the fulcrum at the end. Each blade is a wedge.  
The IMA of a lever would be the length of the handle multiplied by the length of the blade. The IMA of the wedges would be the length of the blade multiplied by its width.
51. A wooden crate is pulled up a ramp that is 1.0 m high and 6.0 m long. The crate is attached to a rope that is wound around an axle with a radius of 0.020 m. The axle is turned by a 0.20 m long handle. What is the overall IMA of the complex machine?
- A. 6  
B. 10  
C. 16  
D. 60