SECTION 8

Work and Power: Getting to the Top

Section Overview

Students investigate the force required to lift a roller-coaster car to a certain height and determine how force, distance, and work are related. They measure the distance a coaster car travels up a ramp and the force applied to pull the car up by keeping the height of the ramp constant, but varying the distance it covers by changing the angle of incline. They record their measurements of force, distance, height, and angle of incline and then measure the force applied to lift a cart vertically. Students note that regardless of the angle of incline, the product of force and distance remains constant. This relationship is illustrated by sketching a graph that shows how force varies with distance. The *Physics Talk* eventually qualifies the relationship between the product of force and distance as the amount of work done on an object. Students finally apply the concept of work to arrive at the definition of power.

Background Information

Work is defined as the product of displacement and the component of the force parallel to the displacement. This product is expressed mathematically as $W = F_{\parallel}d$, where $F_{\parallel}$ is the component of the force parallel to the displacement and d is the displacement. Only the component of the force parallel to the displacement is significant for work. (Work can be written as the vector dot product of force and displacement, where θ is the angle between the force (vector) and the displacement (vector). Since students are unlikely to have met up with dot products in their mathematics courses, it is best to stick with the $F_{\parallel}$ form for work.)

Both force and displacement are vector quantities. They both have direction. Work is a scalar quantity (the dot product between two vectors is often referred to as the scalar product, since in this form of multiplication two vectors result in a scalar). It has no direction but it can be positive or negative. Work is measured in joules, as is energy. Work can be done on an object to increase its kinetic energy. We can see that the force acting when there is a displacement will produce an acceleration (Newton's second law: $F = ma$) and will result in a larger velocity and therefore a larger kinetic energy $\left(KE = \frac{1}{2}mv^2\right)$. Work can also be done on an object to lift it upward, thereby increasing the gravitational potential energy ($GPE = mgh$).

Energy is often defined as the ability to do work. Work is a description of the transfer of energy to or from the system that is providing the force from or to the system on which the force is acting. For example, a force may act on an object causing it to accelerate. As it accelerates, its speed increases and hence its kinetic energy increases. Work is a measure of the energy transferred from the system providing the force to the object, in this case in the form of kinetic energy.

Work can be done on a spring to increase the spring's potential energy $\left(SPE = \frac{1}{2}kx^2\right)$. In turn, the spring can do work on an object and increase the object's *KE* or its *GPE*. In other words, the *SPE* can be transformed into *KE* and/or *GPE*. When no work is done on an object, the object's kinetic energy is conserved (stays constant). When work is done by an outside force, then the object's kinetic energy may increase or decrease. In any closed system (i.e., no external forces), the total energy remains the same, though the energy may change form within the system. This is one of the main organizing principles of physics and is referred to as the conservation of energy. The unit for any form of energy is the joule. Power, measured in watts, is defined as the rate of doing work $\left(\text{Power} = \text{work done / time elapsed or } P = \frac{W}{\Delta t}\right)$.

Crucial Physics

- The work done by a force on an object is the product of displacement of the object and the force acting on the object in the direction of the displacement. The work done on an object is the energy transferred to an object. $W = F \cdot d$, where F is the part of the force acting on the object parallel to the displacement, and d is the displacement of the object. Work, like energy is measured in joules.
- Power is the work done divided by the time elapsed or the rate at which energy is transferred. $P = W/\Delta t$. Power is expressed in joules/second or watts.
- The work done by an object may go toward changing the object's kinetic or potential energy. In a system without dissipative forces, the work done is equal to the change in the energy of the system.

Learning Outcomes	Location in the Section	Evidence of Understanding
Calculate and compare the product of force and distance for lifting an object up a ramp to the same height for different angles of the ramp.	***Investigate*** Steps 1-8	Students roll a cart up a ramp at different angles and measure the force applied with a spring scale. Then they calculate and compare the product of force and distance for the different trials.
Define work in terms of force, F, and displacement, d, in the direction of the force.	***Physics Talk***	Students define work done by a force (F) on an object over a displacement (d) in the following equation: $W = F \cdot d$.
Explain the relationship between work, gravitational potential energy and spring potential energy.	***Physics Talk***	Students should be able to explain that gravitational potential energy of a system increases as the work done on a cart increases, and work done while braking a roller coaster is stored as spring potential energy.
Define power as the rate of doing work, and the units of power are watts.	***Physics Talk***	Students learn that power is the amount of work done divided by the time elapsed.

Section 8 Materials, Preparation, and Safety

Materials and Equipment

PLAN A		
Materials and Equipment	**Group (4 students)**	**Class**
Holder, right angle, cast iron	1 per group	
Rod, aluminum, 3/8 in. x 12 in. (to act as crossarm)	1 per group	
Ring stand, large	1 per group	
Meter stick	1 per group	
Weight, slotted, 12-piece set, 1 g – 500 g	1 per group	
Spring scale, 0-10 N	1 per group	
Ramp, inclined plane (for lab cart)	1 per group	
Cart, carriage (Hall's)	1 per group	
Paper, graph, pkg. of 50		1 per class
Tape, masking		6 per class

*Additional items needed not supplied

Time Requirements

- Allow one class period or 45 minutes for this section's *Investigate*.

Teacher Preparation

- Prepare a Blackline Master of the table the students examine in *Step* 7.
- Set the spring scales to zero before the students use them.
- Test the carts and spring scales you will be using. The cart should weigh close to the full-scale reading when lifted straight up. When the cart is being pulled up the ramp, the scale should read at least one third of the full scale reading for the smaller angle ramps, and around one half for the larger angles for best results. If the carts do not give a reading this large, add masses to the carts until they do.
- Ensure that friction will not play a large role in pulling the carts up the incline.

Safety

- Students should be aware that masses might fall off the carts or that the carts may fall off the table. Make certain that no feet are located below the area where the masses may fall.
- Some dynamics carts have such low friction that they will roll off the table very easily. These carts should be placed upside down on the table until they are ready for use.
- No dynamics carts should be allowed on the floor to prevent someone from slipping on them.

Materials and Equipment

PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Holder, right angle, cast iron		1 per class
Rod, aluminum, 3/8 in. x 12 in. (to act as crossarm)		1 per class
Ring stand, large		1 per class
Meter stick		1 per class
Weight, slotted, 12-piece set, 1 g – 500 g		1 per class
Spring scale, 0-10 N		1 per class
Ramp, inclined plane (for lab cart)		1 per class
Cart, carriage (Hall's)		1 per class
Paper, graph, pkg. of 50		1 per class
Tape, masking		6 per class

*Additional items needed not supplied

Time Requirements

- Allow one class period or 45 minutes for the *Investigate* (all parts), the *Physics Talk* as well as other parts of the section from the *Pacing Guide*.

Teacher Preparation

Note the preparations for Plan A.

- If multiple ramps and carts are available, have several set up at different angles to facilitate a quicker set of measurements. If not, have spots marked out to set the ramp that will provide pre-measured angles and ramp lengths to prevent the need for measurement during the *Investigate*.
- Have a dynamics cart, ramp, spring scale, and meter stick readily available for the whole-class *Investigate*.
- Several students should be recruited to assist you in taking the measurements and recording them on the board for the rest of the class to record in their logs. If a camera and projection system are available they should be used so the students can see more clearly what is occurring.
- Summarize the *Investigate* to familiarize the students with what they will be observing.
- Make Blackline Masters/transparencies of the diagram for *Step 1* and the chart for *Step 7* of the *Investigate* in the *Student Edition*.
- Have a graph of the data for *Investigate, Step 7* pre-made to allow for immediate discussion when placed on an overhead projector or similar device.

Safety

- No dynamics carts should be allowed on the floor to prevent someone from slipping on them.
- Some dynamics carts have such low friction that they will roll off the table very easily. These carts should be placed upside down on the table until they are ready for use.

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Pulling the cart to the same height	***Investigate*** Step 4	**Augmentation** • Students are asked to measure the force and the distance required to pull the same cart to the same height on at least four different angles of incline. Students may confuse height and distance, and this will make it difficult to analyze the data to understand the relationship between force and distance. • Tell students to use another meter stick and use a piece of masking tape to mark the height that the cart must reach before the force and distance are recorded. Then the group members will have assigned jobs, such as the height checker, cart puller/force reader, distance measurer, and the recorder.
Estimating uncertainty of measurements	***Investigate*** Step 5	**Augmentation** • Many students have a difficult time using measurement devices, and these same students often do not have a concept of what the measurements represent. They struggle to compare measurements and to estimate a measurement. • Explain the concept of uncertainty and then provide reasonable amounts of uncertainty that could have occurred during *Step 4*. • Explain the meaning of the (±) symbol because many students have never seen this symbol before and might be confused.
Safely following directions Being literal	***Investigate*** Step 6	**Augmentation** • In *Step 6*, students are asked to lift the cart vertically and must do so with the same mass as when they pulled the cart up the ramp. Remind students to secure the masses to the cart before they lift it vertically. This seems obvious, but students who have very literal language skills might skip this step and get hurt.
Solving problems Choosing formulas	***Physics Talk***	**Augmentation** • At this point in *Chapter 4*, students have learned many new variables, formulas, and units. Help students set up a table to organize the variables, symbols, units, and unit symbols for each formula. Having a one-page reference with this information will help students solve *Physics to Go* problems, and even more importantly, the table will help students with the calculations for the *Chapter Challenge.* • Provide a set of problems that requires students to choose and use different formulas from this chapter. Students become proficient at using a formula when they are asked to solve a few of the same problems in a row, but they often struggle when they are asked to choose the correct formula from a group of formulas. **Accommodation** • Provide a formula table for students to complete, or provide a complete table for students to study.

Strategies for Students with Limited English-Language Proficiency

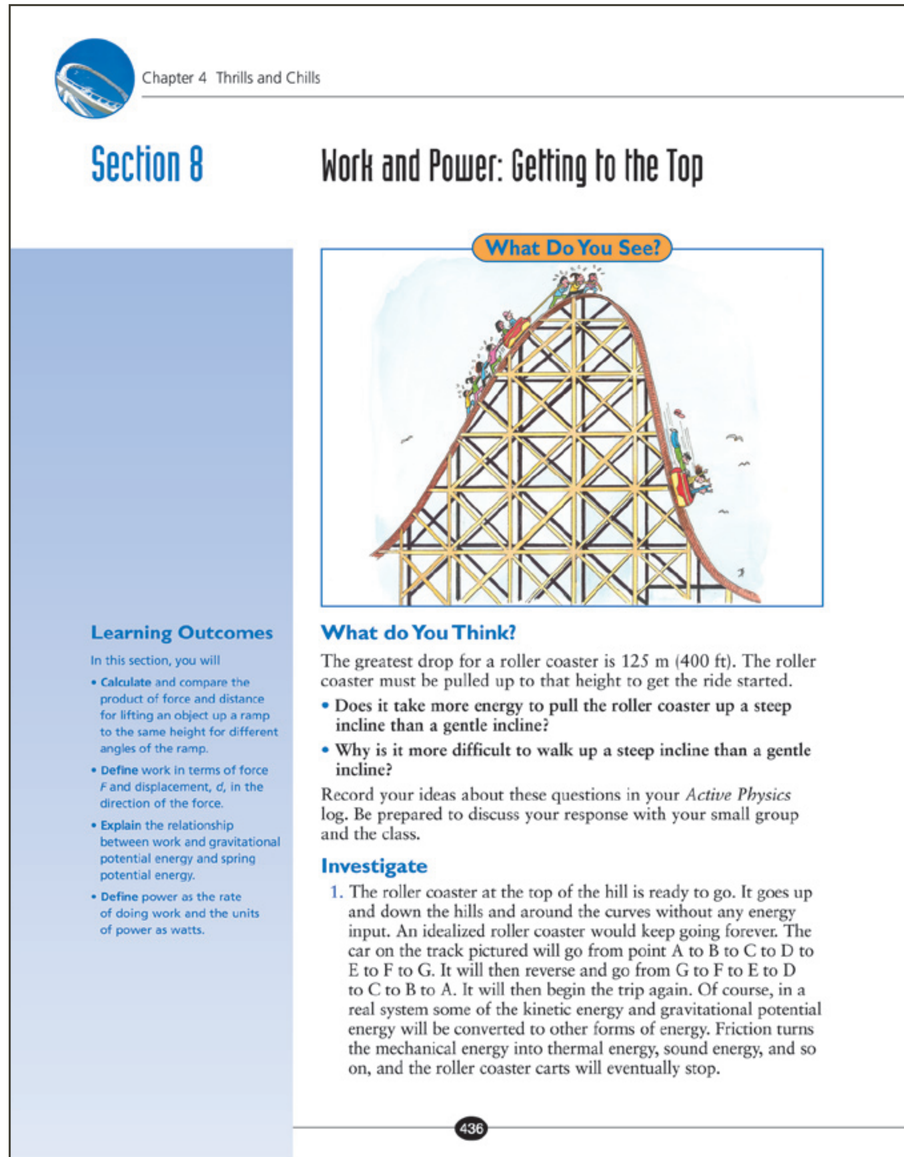
Learning Issue	Reference	Augmentation
Vocabulary comprehension	***Investigate*** Step 3.a)	Review the meaning of the phrase "angle of inclination." It may help to relate the term "inclination" to the term "inclined plane."
Comprehension	***Investigate*** Step 5.a)	Make sure students understand that when recording uncertainty in measurement, the uncertainty accompanies the measurement; it does not replace it. A proper measurement, recorded with uncertainty, will look like this: 43 cm ± 1 cm.
Graphing skills	***Investigate*** Step 8	Review students' graphs to make sure they include a title and labels with units on both axes. Check that the data points are plotted accurately.
Comprehension	***Investigate*** Step 9.e)	To be sure students are correctly grasping the idea of experimental uncertainty, bring the class together to report their measurements. Have each group of students give the difference between their two results, as well as the uncertainly value they recorded. This approach will likely yield some results that agree with the experimental uncertainty and some results that do not agree. By seeing both types of results, students will get a clearer idea of the difference.
Vocabulary comprehension Comprehension	***Physics Talk*** Work, Power	In the definition of "work," make sure students understand the meaning of "displacement." In the definition of "power," make sure students understand the meaning of "elapsed." Review the term "gravitational potential energy." Have an ELL student explain $W = mgh$ in words. Ask another ELL student to explain how this equation represents the work done on a roller-coaster car to raise it to a certain height. Remind students that work also equals force times distance ($W = Fd$), and therefore $Fd = mgh$. Ask a volunteer to explain this relationship.
Understanding concepts	***Physics Talk*** Sample Problem 1	Ask a volunteer to answer this question: If lifting a cart to a height of 12 m requires the same amount of work as sliding the cart up a ramp to a height of 12 m, why does it feel easier to slide the cart? (Less force is required to do the same amount of work, but the force is applied over a longer distance.)
Comprehension	***Physics Talk*** Sample Problem 2	Have an ELL student state the definition of power in words. Students whose native language is not alphabet-based may not recognize certain typographical treatments we give to English letters and words. To help students see the difference between W (watts) and *W* (work), explain italic (slanted) type. Sometimes italic type is used for emphasis; other times, as here, it is used to designate a variable.

SECTION 8

Teaching Suggestions and Sample Answers

What Do You See?

The illustration in this section clearly shows how hard it is for the roller-coaster car to be pushed up a steep hill, but easy for it to slide down. Students' answers will provide you with clues to what they know about work and power. In your discussion, bring in the terms, force, work, and power in relation to the visuals that the students see. The *What Do You See?* illustration evokes a stimulating discussion and prompts students to respond informally. A relaxed class environment promotes students engagement and this section hooks students' attention and gets them involved in the topics they are about to learn. You should keep students engaged in interpreting the illustration, but at the same time give them the space to answer with unrestrained energy. Let students know that they will have an opportunity to revisit this section.



Chapter 4 Thrills and Chills

Section 8 Work and Power: Getting to the Top

What Do You See?

Learning Outcomes

In this section, you will

- **Calculate** and compare the product of force and distance for lifting an object up a ramp to the same height for different angles of the ramp.
- **Define** work in terms of force *F* and displacement, *d*, in the direction of the force.
- **Explain** the relationship between work and gravitational potential energy and spring potential energy.
- **Define** power as the rate of doing work and the units of power as watts.

What do You Think?

The greatest drop for a roller coaster is 125 m (400 ft). The roller coaster must be pulled up to that height to get the ride started.

- **Does it take more energy to pull the roller coaster up a steep incline than a gentle incline?**
- **Why is it more difficult to walk up a steep incline than a gentle incline?**

Record your ideas about these questions in your *Active Physics* log. Be prepared to discuss your response with your small group and the class.

Investigate

1. The roller coaster at the top of the hill is ready to go. It goes up and down the hills and around the curves without any energy input. An idealized roller coaster would keep going forever. The car on the track pictured will go from point A to B to C to D to E to F to G. It will then reverse and go from G to F to E to D to C to B to A. It will then begin the trip again. Of course, in a real system some of the kinetic energy and gravitational potential energy will be converted to other forms of energy. Friction turns the mechanical energy into thermal energy, sound energy, and so on, and the roller coaster carts will eventually stop.

436

Students' Prior Conceptions

The following prior conception is critical in hindering student understanding of work:

Students believe that force times any distance is work; they do not believe that the force acting on the object and the displacement must be parallel to each other. The data and energy calculations for the work needed to pull a cart up a ramp to the same height regardless of the angle of the ramp informs students that work is the product of the force acting parallel to the ramp multiplied by the displacement. Students can extend this pattern to comprehend how only the component of a force parallel to the displacement of an object does work upon that object.

What Do You Think?

Students should be encouraged to recall the physics concepts they have learned so far, and incorporate their understanding of force and energy in their answers. Remind them that they will be updating their responses later on and at this time they should record their ideas without worrying about how "right" or "wrong" they are. You might want to ask students if they remember their experience climbing up a steep incline and how they would compare it to their experience of climbing a gentle incline. The *What Do You Think?* questions give you the chance of assessing how students are utilizing prior knowledge and what misconceptions they might have.

What Do You Think?

A Physicist's Response

Although the energy required is identical, irrespective of the slope of the incline (as long as friction is not important), it is common for students to think that a steep incline requires more energy. This is probably because they confuse energy with force. A gentle incline does not require as much force as a steep incline. As the angle of the incline increases, a larger force is required to get to the same height because the distance traveled along the incline is so much less. The total work done is the same, but since the work is usually done in a shorter time period for a steep slope than a gradual one, greater power would be necessary for the steep slope. It is the larger force that our bodies feel, and the greater power required that leaves us tired more quickly.

NOTES

NOTES

Investigate

1.a)

The roller coaster has a total mechanical energy determined by the height of the first hill. For the roller coaster to get to a larger height, it would need additional energy. A more formal way of looking at this is to realize that if the final potential energy ($GPE = mgh$) were greater than the initial gravitational potential energy, then the kinetic energy would have to be less than the initial kinetic energy. The kinetic energy at the first hill was zero, and kinetic energy can never be less than zero because it is always a positive quantity. In the equation for kinetic energy, $KE = \frac{1}{2}mv^2$, the mass is always positive and the square of the velocity must also be positive.

4-8a **Blackline Master**

2.

Height of top of ramp = ________

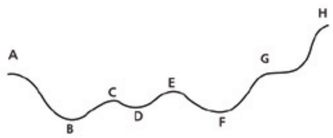
Remind the students to use the same height above the table for each trial.

2.a)

The data table should include the ramp angle, the height of the support near the top of the ramp, the length of the ramp from the bottom to the support height, and the force required to move the cart up the track at constant speed.

2.b)

Make sure the students are pulling the carts by applying the force parallel to the track. The easiest way for the students to tell if the speed is constant is if the reading on the spring scale is constant, and the cart is not accelerating.



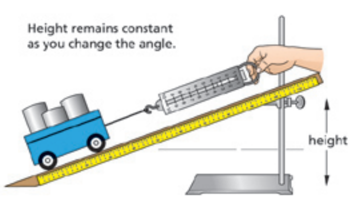
a) Why do you think that the roller coaster cannot scale a higher hill than the one from which it began?

2. You will now investigate the force required to lift a roller-coaster cart to a certain height. You will use a cart and a ramp in your classroom. You can pull the cart to the top of the ramp with the use of a spring scale. The spring scale will indicate the force required to pull the cart.

   A meter stick can be used to record the distance that the cart moved along the ramp. You can then vary the distance along the ramp by varying the ramp angle *while keeping the height to which you raise the cart the same.*

   The ramp should be measured from the bottom of the ramp to the height of the support for the ramp.

Be careful when lifting and lowering the weight, as it could cause injury if it were to fall. Make smooth, unhurried movements.



a) Create a data table in which you can record the force required to pull the cart up the ramp the four different distances at the four different angles.

b) Measure the force required to pull the cart up the ramp to a specified height at constant speed. Reminder: You must always pull the cart to the same height and parallel to the ramp. How will you determine if the speed is constant?

c) Measure the distance that the cart travels along the ramp from the bottom to the specified height.

3. Complete your investigation.

a) Record your information in your data table.

b) What conclusion can you reach about the force required to move the cart and the distance the cart moves along the ramp to attain a specific height?

4. Any time you take measurements, there is some uncertainty in the measurement. When you weigh yourself on a scale, the weight reading may be off by a little bit. If the scale reads 143 lb, you may actually weigh 143 lb and a few ounces. The scale does not give you an exact measurement. No measurement is ever exact.

a) What are the uncertainties in your measurements of distance? Could your measurement of distance be off by as much as 3 cm? Could your measurement of distance be off by as much as 1 cm? What is the largest amount that your distance measurement may be off? Write down this value with the notation ± to signify that you may have been under or over by that amount. For instance, if you think that your distance measurement could have been off by 2 cm, you would write this as ±2 cm.

2.c)

Make certain the students measure the distance from the end of the ramp on the table up to only the support bar, and not the total length of the ramp.

Teaching Tip

As the angle increases, the distance they pull it will decrease. The students should be reminded to pull on the carts parallel to the plane.

3.a)

A data table like the one shown in the next column would work well. In *Step 8.a)*, students will record the product of force and distance in the third column of their table.

distance	force	

3.b)

As the distance along the ramp increases (because of the change in angle of the ramp), the force required to pull the cart up the ramp becomes smaller.

4.a)

The students should be able to measure the distance with an uncertainty less than 1 cm.

CHAPTER 4

4.b)

The uncertainty in force measurements will depend on the sensitivity of the spring scale used and how steadily the students are able to pull the cart up the track.

5.a)

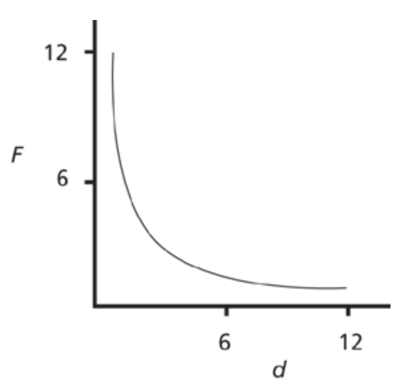
When the students lift the cart vertically, the force exerted by the spring scale should be equal to the weight of the cart.

6.a)

An electric motor, as mentioned, is one possibility. A gasoline engine might be used. You could have horses pulling on ropes to get the cart to the top. Many, many other answers are acceptable.

7.a)

The students should find that longer distances (smaller track angles) require smaller forces. The students' graph should look similar to the one below.



8.

Students' graph should be similar in shape to the one above.

8.a)

Students' answers will vary depending on their data. The product of force and distance should be a constant. Students could record the product of force and distance in the third column of their chart in *Step 3*.

8.b)

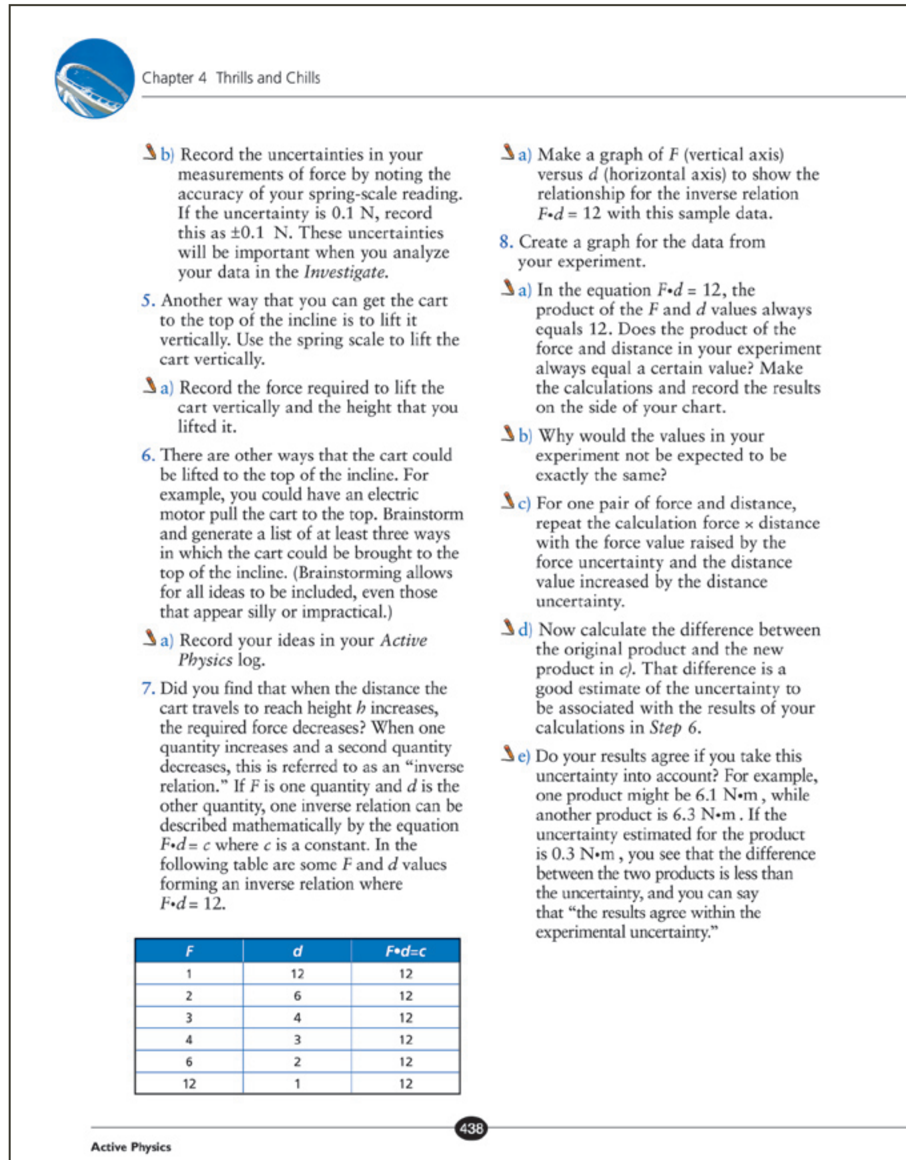
Uncertainty in the values for force and distance could account for some discrepancies (measurements always have uncertainties). Also, friction may not be entirely insignificant for the carts.

8.c)

Using values from the chart in *Step 7* as an example, the force may be 6 when the distance is 2. Assume the uncertainties in these measurements are 0.1 for both force and distance. Adding the uncertainties to these values would give 6.1 for force and 2.1 for distance. The product of force and distance then would be 12.8, rather than 12 for 6 and 2.

8.d)

The difference in the values from *Step 8.c)* is $12.8 - 12 = 0.8$ or about 6%. The spread in



Chapter 4 Thrills and Chills

b) Record the uncertainties in your measurements of force by noting the accuracy of your spring-scale reading. If the uncertainty is 0.1 N, record this as ±0.1 N. These uncertainties will be important when you analyze your data in the *Investigate*.

5. Another way that you can get the cart to the top of the incline is to lift it vertically. Use the spring scale to lift the cart vertically.

a) Record the force required to lift the cart vertically and the height that you lifted it.

6. There are other ways that the cart could be lifted to the top of the incline. For example, you could have an electric motor pull the cart to the top. Brainstorm and generate a list of at least three ways in which the cart could be brought to the top of the incline. (Brainstorming allows for all ideas to be included, even those that appear silly or impractical.)

a) Record your ideas in your *Active Physics* log.

7. Did you find that when the distance the cart travels to reach height h increases, the required force decreases? When one quantity increases and a second quantity decreases, this is referred to as an "inverse relation." If F is one quantity and d is the other quantity, one inverse relation can be described mathematically by the equation $F \cdot d = c$ where c is a constant. In the following table are some F and d values forming an inverse relation where $F \cdot d = 12$.

F	d	$F \cdot d = c$
1	12	12
2	6	12
3	4	12
4	3	12
6	2	12
12	1	12

a) Make a graph of F (vertical axis) versus d (horizontal axis) to show the relationship for the inverse relation $F \cdot d = 12$ with this sample data.

8. Create a graph for the data from your experiment.

a) In the equation $F \cdot d = 12$, the product of the F and d values always equals 12. Does the product of the force and distance in your experiment always equal a certain value? Make the calculations and record the results on the side of your chart.

b) Why would the values in your experiment not be expected to be exactly the same?

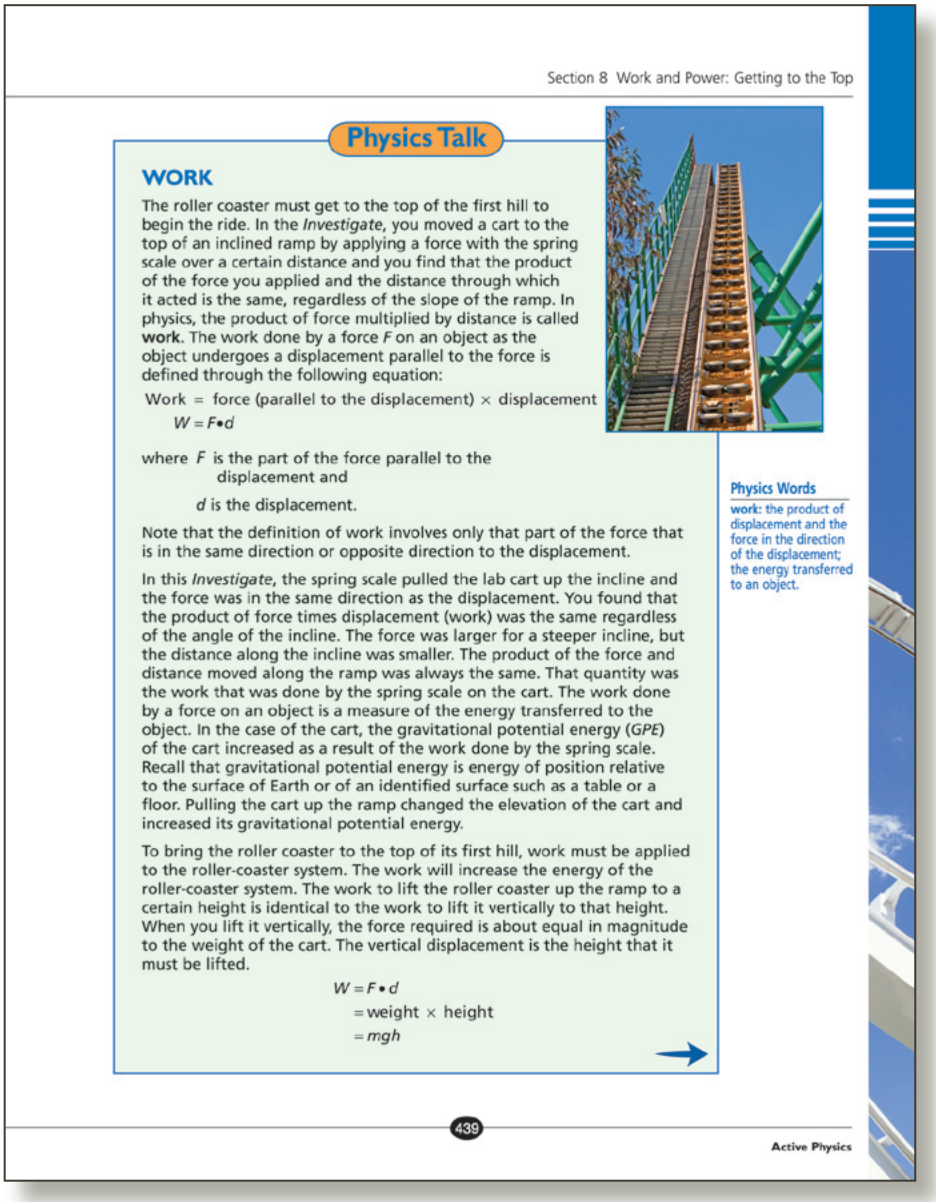
c) For one pair of force and distance, repeat the calculation force × distance with the force value raised by the force uncertainty and the distance value increased by the distance uncertainty.

d) Now calculate the difference between the original product and the new product in *c)*. That difference is a good estimate of the uncertainty to be associated with the results of your calculations in *Step 6*.

e) Do your results agree if you take this uncertainty into account? For example, one product might be 6.1 N•m, while another product is 6.3 N•m. If the uncertainty estimated for the product is 0.3 N•m, you see that the difference between the two products is less than the uncertainty, and you can say that "the results agree within the experimental uncertainty."

438

Active Physics



values gives an estimate of the uncertainty to be associated with the results.

8.e)

Agreeing within the quantitative experimental uncertainty is the best we can expect for a set of measured values.

Another way to estimate the uncertainty: Distance measurements made with a ruler usually have uncertainties of at least 0.1 cm. The uncertainty in distance may be as large as 0.5 cm. Uncertainties in force could be as much as 1 N. Suppose that the force = 2 N and the distance is 0.30 m. Suppose the uncertainty in the force is ± 0.1 N and the uncertainty in the distance is ± 0.005 m. The largest product of force and distance could be $2.1\ \text{N} \times 0.305\ \text{m} = 0.6405\ \text{J}$. The smallest the product could be is $1.9\ \text{N} \times 0.295\ \text{m} = 0.5605\ \text{J}$.

The difference between the two results is $0.6405\ \text{J} - 0.5605\ \text{J} = 0.08\ \text{J}$. So we could use 0.08 J as an estimate of the uncertainty in the work. You would write $W = 0.60 \pm 0.08\ \text{J}$.

4-8b **Blackline Master**

Physics Talk

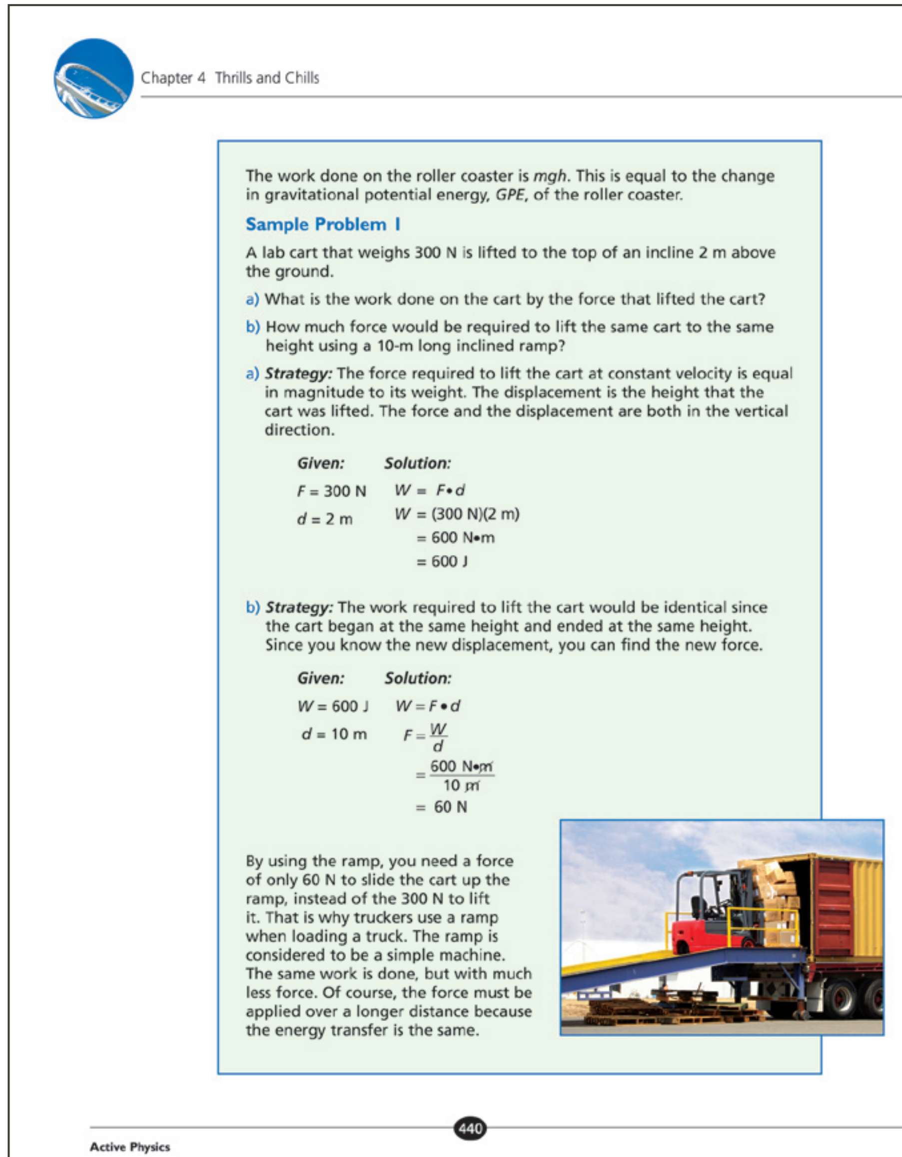
The observations in the *Investigate* are related to the work done on a roller coaster. The *Physics Talk* provides the definition of work and shows how rolling an object up an incline, regardless of the slope of the incline, results in the same amount of work. Stated another way, for a conservative force (one with out losses), the work done is independent of the path. Students should be required to enter the work equation into their *Active Physics* logs. They should also note that the product of force and distance moved along the ramp was always the same when the cart is raised to the same height. Ask students how energy is related to work. Revisit the definition of gravitational potential energy (*GPE*), making sure that students know how increasing the work done increases the amount of *GPE* relative to the surface of Earth. Point out that in order to bring the roller coaster to the top of the hill, force has to be applied over a certain distance. This increases the amount of work done, which in turn increases the gravitational potential energy of the roller coaster.

CHAPTER 4

As students read how work and energy are related, emphasize that a roller coaster would require a lot of energy to lift it up a hill but there would be no difference in the amount of work done if it reached the same height by climbing vertically, instead of on a ramp. Discuss how the sample problem shows that the amount of force applied varies with the angle of the incline, but the work done remains the same.

How energy is transferred as the roller coaster ascends and then descends a hill is an essential part of understanding the principle of conservation of energy. Discuss how energy is supplied to a roller coaster, how it gains energy, and how it loses some of its energy to the environment. Ask students to describe the different methods that can be used to make the roller coasters gain energy and how they would calculate the energy that is supplied. Determine if students know what forms of energy are lost as the roller coaster goes up and down.

Draw students' attention to the braking system of a roller coaster. Emphasize that brakes convert the *KE* of the coaster cars to thermal energy. Find out if students understand how kinetic energy of the cars is stored as the spring's potential energy if a spring is used to stop the coaster car rather than brakes. As the *Physics Talk* progresses to the definition of power, highlight the definition of power by writing its mathematical equation on the board.



Chapter 4 Thrills and Chills

The work done on the roller coaster is *mgh*. This is equal to the change in gravitational potential energy, *GPE*, of the roller coaster.

Sample Problem I

A lab cart that weighs 300 N is lifted to the top of an incline 2 m above the ground.

a) What is the work done on the cart by the force that lifted the cart?

b) How much force would be required to lift the same cart to the same height using a 10-m long inclined ramp?

a) ***Strategy:*** The force required to lift the cart at constant velocity is equal in magnitude to its weight. The displacement is the height that the cart was lifted. The force and the displacement are both in the vertical direction.

Given:
$F = 300$ N
$d = 2$ m

Solution:
$$W = F \cdot d$$
$$W = (300\text{ N})(2\text{ m}) = 600\text{ N}\cdot\text{m} = 600\text{ J}$$

b) ***Strategy:*** The work required to lift the cart would be identical since the cart began at the same height and ended at the same height. Since you know the new displacement, you can find the new force.

Given:
$W = 600$ J
$d = 10$ m

Solution:
$$W = F \cdot d$$
$$F = \frac{W}{d} = \frac{600\text{ N}\cdot\cancel{\text{m}}}{10\text{ }\cancel{\text{m}}} = 60\text{ N}$$

By using the ramp, you need a force of only 60 N to slide the cart up the ramp, instead of the 300 N to lift it. That is why truckers use a ramp when loading a truck. The ramp is considered to be a simple machine. The same work is done, but with much less force. Of course, the force must be applied over a longer distance because the energy transfer is the same.

440

Active Physics

Have students enter the unit of power and its definition in their logs and discuss the sample problem that shows how work and power are related but are different quantities and have different units.

More Roller-Coaster Energy

The roller-coaster car is usually raised with electrical energy supplied by a motor. Electrical energy can be calculated by measuring the voltage, current, and time. Creating steam to push it up the incline could also have raised the roller-coaster cart. In this method, the heat energy can also be calculated. In all of these methods, work is done by the spring, by the electricity, or by the heat. The roller-coaster system gains that amount of energy. The roller coaster has increased its *GPE* by that amount.

In any system, the total energy remains the same. This is an organizing principle of physics and is referred to as the conservation of energy.

Although you treat the roller-coaster's energy as primarily *KE* and *GPE*, real roller coasters have some energy transferred to other forms such as heat energy and sound energy. There is work done by friction and work done by air resistance. This work removes *KE* and *GPE* from the roller coaster. The work done by friction, for instance, becomes heat energy that is dissipated into the air surrounding the roller coaster.

Braking the Roller Coaster

Your roller coaster must have a means of stopping the cars at the end of the ride. Normally, brakes stop the coaster cars. The brakes use friction to convert the *KE* of the car's motion into thermal energy. The brakes might fail; so you need to have a back-up mechanism to stop the coaster cars. One way to do this is to have a large spring that the car can compress. As the spring is compressed, the *KE* of the cars is stored as spring potential energy. The expression for spring potential energy is $\frac{1}{2}kx^2$, where x is the distance that the springs are stretched or compressed.

Power

Sometimes it is important to know how fast work is done. In this *Investigate*, you pulled the lab cart up the incline. You could have pulled it up with a variety of speeds. To take the time into account, you divide the work done by the time elapsed. The result is called **power**. The definition of power is

$$\text{power} = \frac{\text{work done}}{\text{time elapsed}}$$

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

Note that the scientific definition of power is different from the ordinary usage of the word in sentences like, "I have power over you," or "She has lots of political power."

Physics Words

power: the work done divided by the time elapsed; the speed at which work is done and energy is transferred.

Checking Up

1.

The energy has gone into the coaster car and is stored as gravitational potential energy.

2.

The roller coaster gains its gravitational potential energy from an electrical motor.

3.

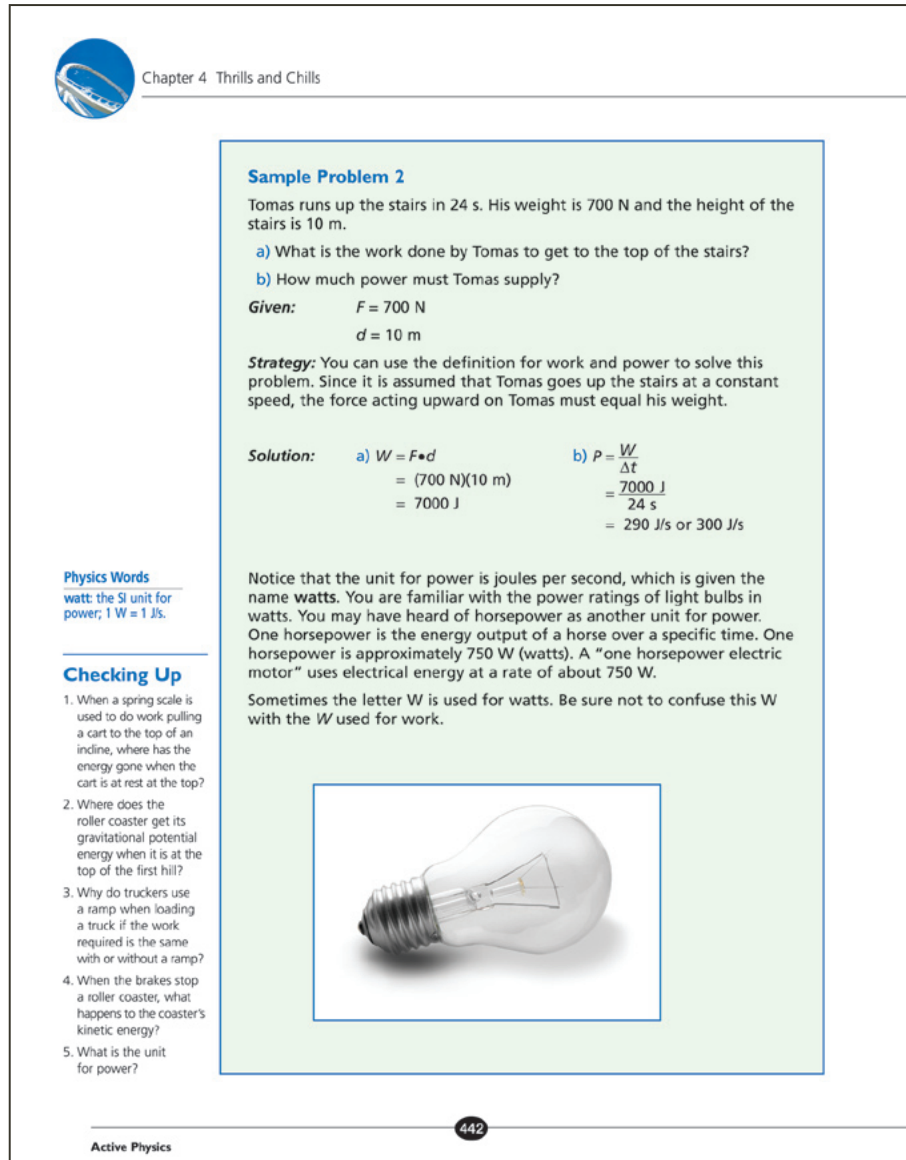
Truckers use a ramp to reduce the amount of force they have to apply while lifting the load.

4.

The coaster's kinetic energy is stored as the spring potential energy.

5.

The unit for power is watt (W).



Chapter 4 Thrills and Chills

Sample Problem 2

Tomas runs up the stairs in 24 s. His weight is 700 N and the height of the stairs is 10 m.

a) What is the work done by Tomas to get to the top of the stairs?

b) How much power must Tomas supply?

Given: $F = 700$ N

$d = 10$ m

Strategy: You can use the definition for work and power to solve this problem. Since it is assumed that Tomas goes up the stairs at a constant speed, the force acting upward on Tomas must equal his weight.

Solution:

a) $W = F \bullet d$
$= (700\text{ N})(10\text{ m})$
$= 7000\text{ J}$

b) $P = \frac{W}{\Delta t}$
$= \frac{7000\text{ J}}{24\text{ s}}$
$= 290\text{ J/s or }300\text{ J/s}$

Physics Words

watt: the SI unit for power; 1 W = 1 J/s.

Notice that the unit for power is joules per second, which is given the name **watts**. You are familiar with the power ratings of light bulbs in watts. You may have heard of horsepower as another unit for power. One horsepower is the energy output of a horse over a specific time. One horsepower is approximately 750 W (watts). A "one horsepower electric motor" uses electrical energy at a rate of about 750 W.

Sometimes the letter W is used for watts. Be sure not to confuse this W with the *W* used for work.

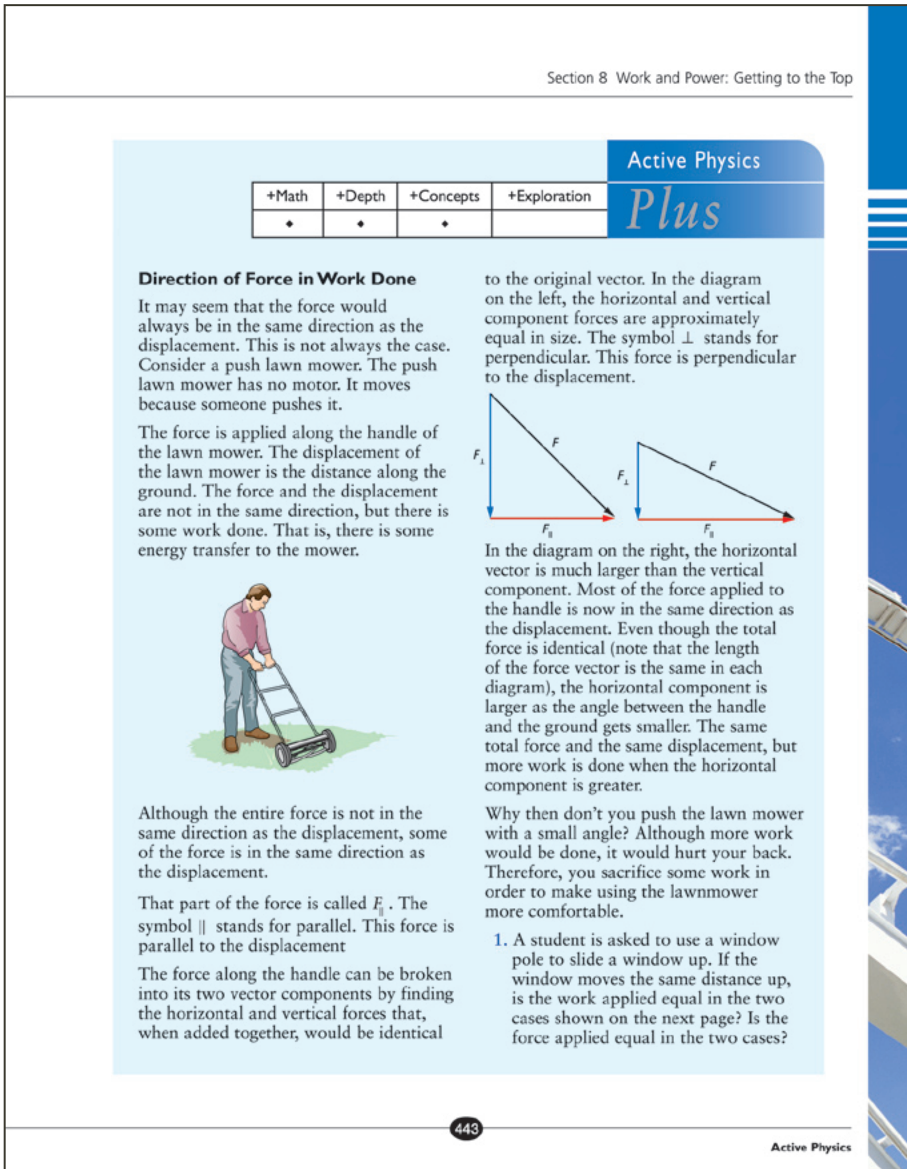
Checking Up

1. When a spring scale is used to do work pulling a cart to the top of an incline, where has the energy gone when the cart is at rest at the top?
2. Where does the roller coaster get its gravitational potential energy when it is at the top of the first hill?
3. Why do truckers use a ramp when loading a truck if the work required is the same with or without a ramp?
4. When the brakes stop a roller coaster, what happens to the coaster's kinetic energy?
5. What is the unit for power?

442

Active Physics

potential energy. The boy on the right exerts less force to move the window because more of the force he is exerting is being applied parallel to the direction of motion of the window. Likewise, less force is being applied perpendicular to the motion, which does no work on the window. In both cases, the work done goes to increasing the gravitational potential energy of the window. It should be pointed out that one of the reasons so much more force is required by the boy on the left to move the window is friction. Because the frictional force depends on pushing the pole in a more perpendicular direction than parallel to the window, the normal force, and thus the friction between the window and the frame is increased.



Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
◆	◆	◆	

Direction of Force in Work Done

It may seem that the force would always be in the same direction as the displacement. This is not always the case. Consider a push lawn mower. The push lawn mower has no motor. It moves because someone pushes it.

The force is applied along the handle of the lawn mower. The displacement of the lawn mower is the distance along the ground. The force and the displacement are not in the same direction, but there is some work done. That is, there is some energy transfer to the mower.

Although the entire force is not in the same direction as the displacement, some of the force is in the same direction as the displacement.

That part of the force is called $F_{\parallel}$. The symbol $\parallel$ stands for parallel. This force is parallel to the displacement

The force along the handle can be broken into its two vector components by finding the horizontal and vertical forces that, when added together, would be identical to the original vector. In the diagram on the left, the horizontal and vertical component forces are approximately equal in size. The symbol $\perp$ stands for perpendicular. This force is perpendicular to the displacement.

In the diagram on the right, the horizontal vector is much larger than the vertical component. Most of the force applied to the handle is now in the same direction as the displacement. Even though the total force is identical (note that the length of the force vector is the same in each diagram), the horizontal component is larger as the angle between the handle and the ground gets smaller. The same total force and the same displacement, but more work is done when the horizontal component is greater.

Why then don't you push the lawn mower with a small angle? Although more work would be done, it would hurt your back. Therefore, you sacrifice some work in order to make using the lawnmower more comfortable.

1. A student is asked to use a window pole to slide a window up. If the window moves the same distance up, is the work applied equal in the two cases shown on the next page? Is the force applied equal in the two cases?

Active Physics Plus

Direction of Forces in Work Done

Depending on the distance the force is applied, the amount of work done can be less or more. Students explore the concept of force vectors through diagrams and by solving problems. They learn how the force applied at an angle can sometimes be in two directions, which are the horizontal and vertical components of that force. They also explore how spring potential energy can be converted to kinetic energy.

1.

Both boys will be doing the same amount of work (neglecting work done against friction), since the window moves up the same distance and gains the same amount of gravitational

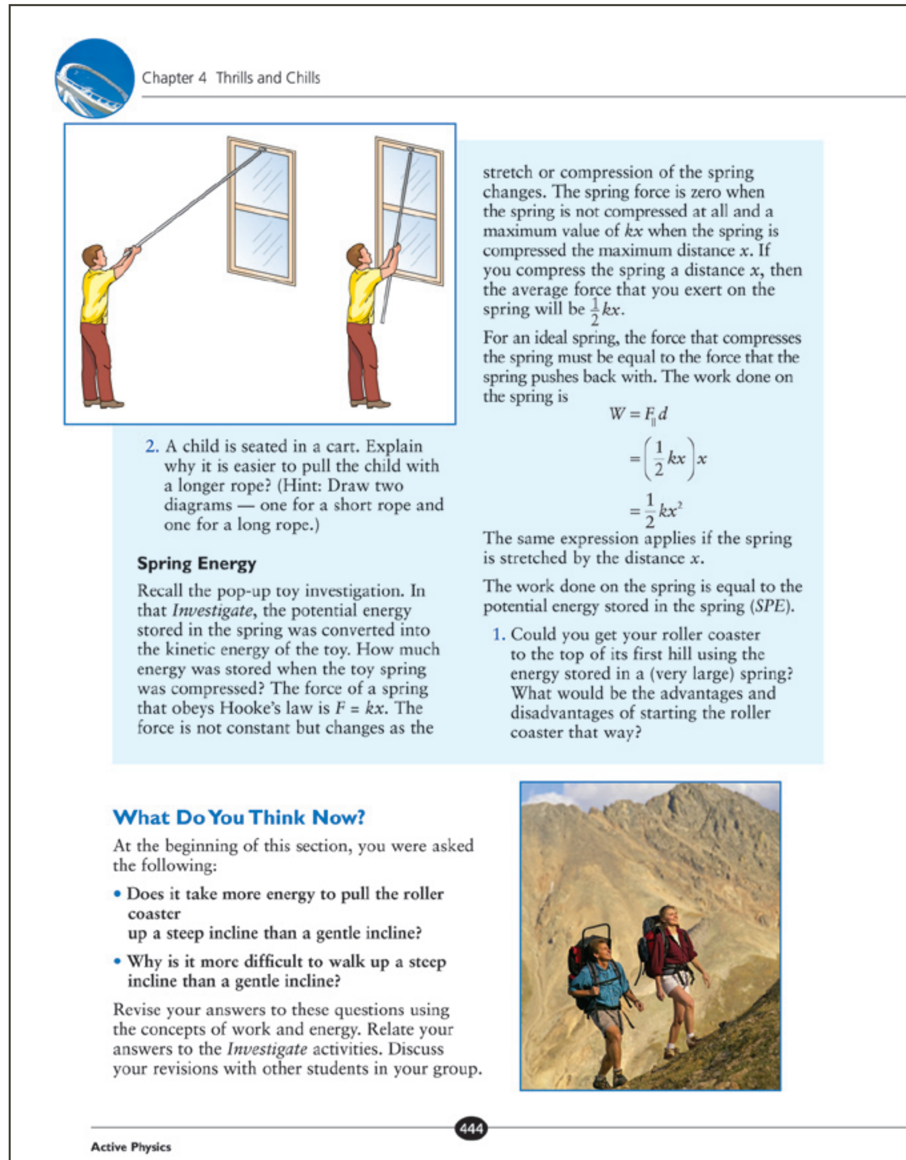
2.

With a longer rope, more of the force is exerted parallel to the direction of motion so less force is needed for the same amount of work. Consider an extreme case where someone pulls vertically upward on the rope. This would exert no force forward on the cart, so the cart would not move, and no work would be done.

Spring Energy

1.

Yes, you could use a very large spring to propel the riders to the top of the first hill. One advantage to doing things this way is you could turn the spring around after the cart is on its way and use it to stop the cart when it returned to recapture the energy used to get the roller coaster going. A big disadvantage would be that the force of the spring is largest at maximum compression. This means the riders would have a very large acceleration as the ride first starts, and go slower and slower until the cart reaches the top of the first hill. The large initial acceleration might lead to whiplash for some riders, and then the slowing ascent might be anti-climactic.



2. A child is seated in a cart. Explain why it is easier to pull the child with a longer rope? (Hint: Draw two diagrams — one for a short rope and one for a long rope.)

Spring Energy

Recall the pop-up toy investigation. In that *Investigate*, the potential energy stored in the spring was converted into the kinetic energy of the toy. How much energy was stored when the toy spring was compressed? The force of a spring that obeys Hooke's law is $F = kx$. The force is not constant but changes as the stretch or compression of the spring changes. The spring force is zero when the spring is not compressed at all and a maximum value of kx when the spring is compressed the maximum distance x. If you compress the spring a distance x, then the average force that you exert on the spring will be $\frac{1}{2}kx$.

For an ideal spring, the force that compresses the spring must be equal to the force that the spring pushes back with. The work done on the spring is

$$W = F_{\parallel} d$$
$$= \left(\frac{1}{2}kx\right)x$$
$$= \frac{1}{2}kx^2$$

The same expression applies if the spring is stretched by the distance x.

The work done on the spring is equal to the potential energy stored in the spring (*SPE*).

1. Could you get your roller coaster to the top of its first hill using the energy stored in a (very large) spring? What would be the advantages and disadvantages of starting the roller coaster that way?

What Do You Think Now?

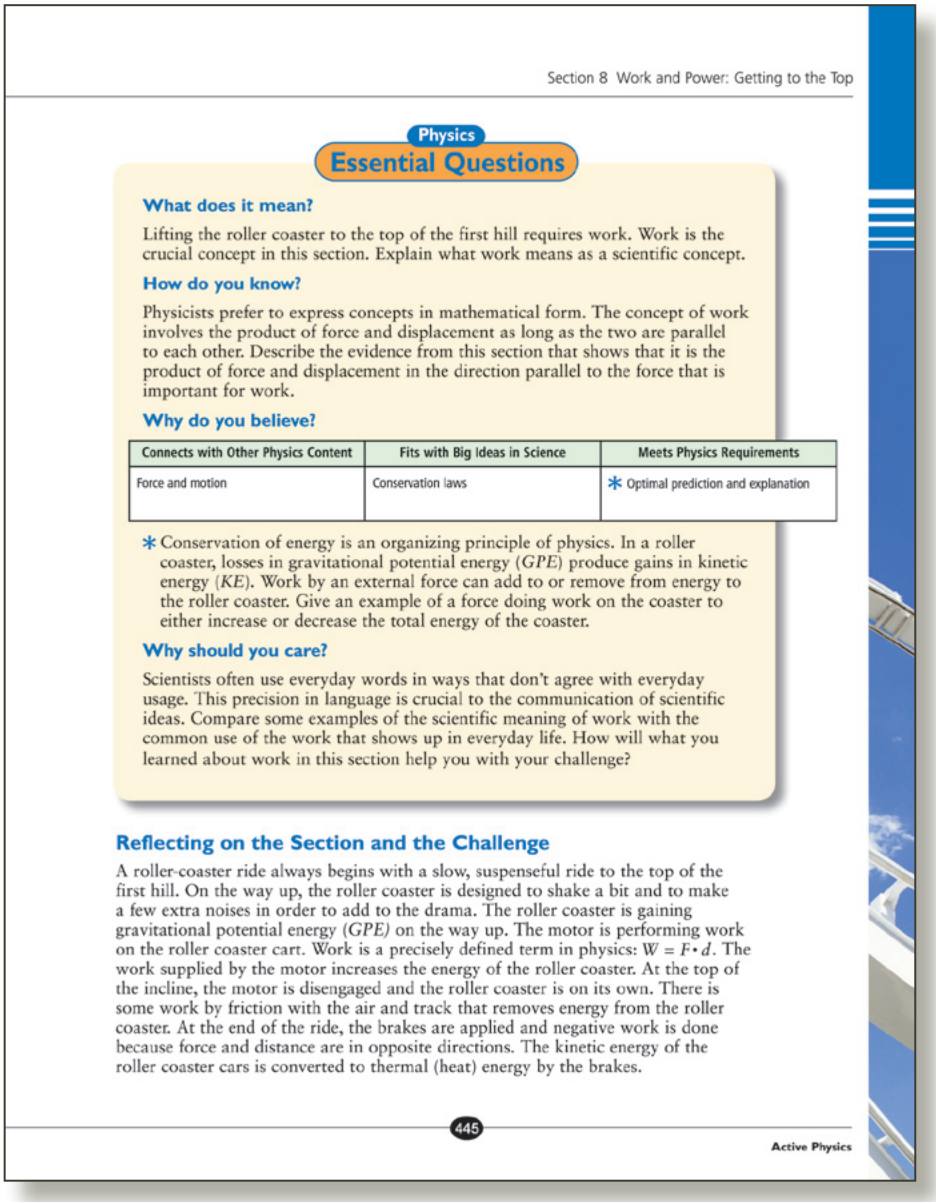
At the beginning of this section, you were asked the following:

- **Does it take more energy to pull the roller coaster up a steep incline than a gentle incline?**
- **Why is it more difficult to walk up a steep incline than a gentle incline?**

Revise your answers to these questions using the concepts of work and energy. Relate your answers to the *Investigate* activities. Discuss your revisions with other students in your group.

What Do You Think Now?

Ask students to revisit the *What Do You See?* and *What Do You Think?* sections and use their present information to revise their original responses. Emphasize that they should relate their answers to their *Investigates*. Have them share their answers and discuss the key aspects of *A Physicist's Response*. Encourage students to share their doubts and review the commonly held misconceptions about work, energy, and power. Stress how important it is to address prior conceptions about physics concepts that students are studying and check them against what they have added to their previous knowledge. Reiterate that asking questions and clarifying doubts is part of the scientific process and leads to a better grasp of concepts.



Physics

Essential Questions

What does it mean?

Lifting the roller coaster to the top of the first hill requires work. Work is the crucial concept in this section. Explain what work means as a scientific concept.

How do you know?

Physicists prefer to express concepts in mathematical form. The concept of work involves the product of force and displacement as long as the two are parallel to each other. Describe the evidence from this section that shows that it is the product of force and displacement in the direction parallel to the force that is important for work.

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Force and motion	Conservation laws	* Optimal prediction and explanation

* Conservation of energy is an organizing principle of physics. In a roller coaster, losses in gravitational potential energy (*GPE*) produce gains in kinetic energy (*KE*). Work by an external force can add to or remove from energy to the roller coaster. Give an example of a force doing work on the coaster to either increase or decrease the total energy of the coaster.

Why should you care?

Scientists often use everyday words in ways that don't agree with everyday usage. This precision in language is crucial to the communication of scientific ideas. Compare some examples of the scientific meaning of work with the common use of the work that shows up in everyday life. How will what you learned about work in this section help you with your challenge?

Reflecting on the Section and the Challenge

A roller-coaster ride always begins with a slow, suspenseful ride to the top of the first hill. On the way up, the roller coaster is designed to shake a bit and to make a few extra noises in order to add to the drama. The roller coaster is gaining gravitational potential energy (*GPE*) on the way up. The motor is performing work on the roller coaster cart. Work is a precisely defined term in physics: $W = F \cdot d$. The work supplied by the motor increases the energy of the roller coaster. At the top of the incline, the motor is disengaged and the roller coaster is on its own. There is some work by friction with the air and track that removes energy from the roller coaster. At the end of the ride, the brakes are applied and negative work is done because force and distance are in opposite directions. The kinetic energy of the roller coaster cars is converted to thermal (heat) energy by the brakes.

Reflecting on the Section and the Challenge

Consider asking a student to read this section aloud. While the student is reading the passage aloud, highlight important words and phrases that can bring together the different concepts students have learned. Draw students' attention to the suspense that is built as the roller coaster goes up. You might want to ask students why work is a term that is defined in physics and have them reflect on its definition. Point out that the force of air friction on the moving car and friction between the car and the track are doing work on the roller coaster that removes energy from the system. Discuss how kinetic energy is changed to thermal energy and the work done is negative when the brakes are applied. Reiterate that this energy is then lost to the environment, and not recoverable as spring potential energy would be. Ask students to use this information to meet the criteria of their *Chapter Challenge*.

Physics Essential Questions

What does it mean?

Work is defined as the product of a force over a given displacement. The force (or a component of the force) must be in the same direction as the displacement for work to be done.

How do you know?

The work in lifting a mass to the top of an incline was equivalent for all variations of the ramp. As the angle of the ramp changed, both the displacement and force along the ramp changed such that the product was still constant.

Why do you believe?

Lifting the roller coaster to its initial height provides the coaster with gravitational potential energy (*GPE*). This gain in *GPE* is due to the work done on the coaster by the motor.

Why should you care?

Work in physics has a specific definition and specific units: N•m or J. Work in everyday language can mean many things. A person can work for three hours. Work in physics never has the units of time.

Physics to Go

1.a)
The *GPE* decreases as the cart descends the ramp.

1.b)
$W = F_{\parallel}d = mgh$

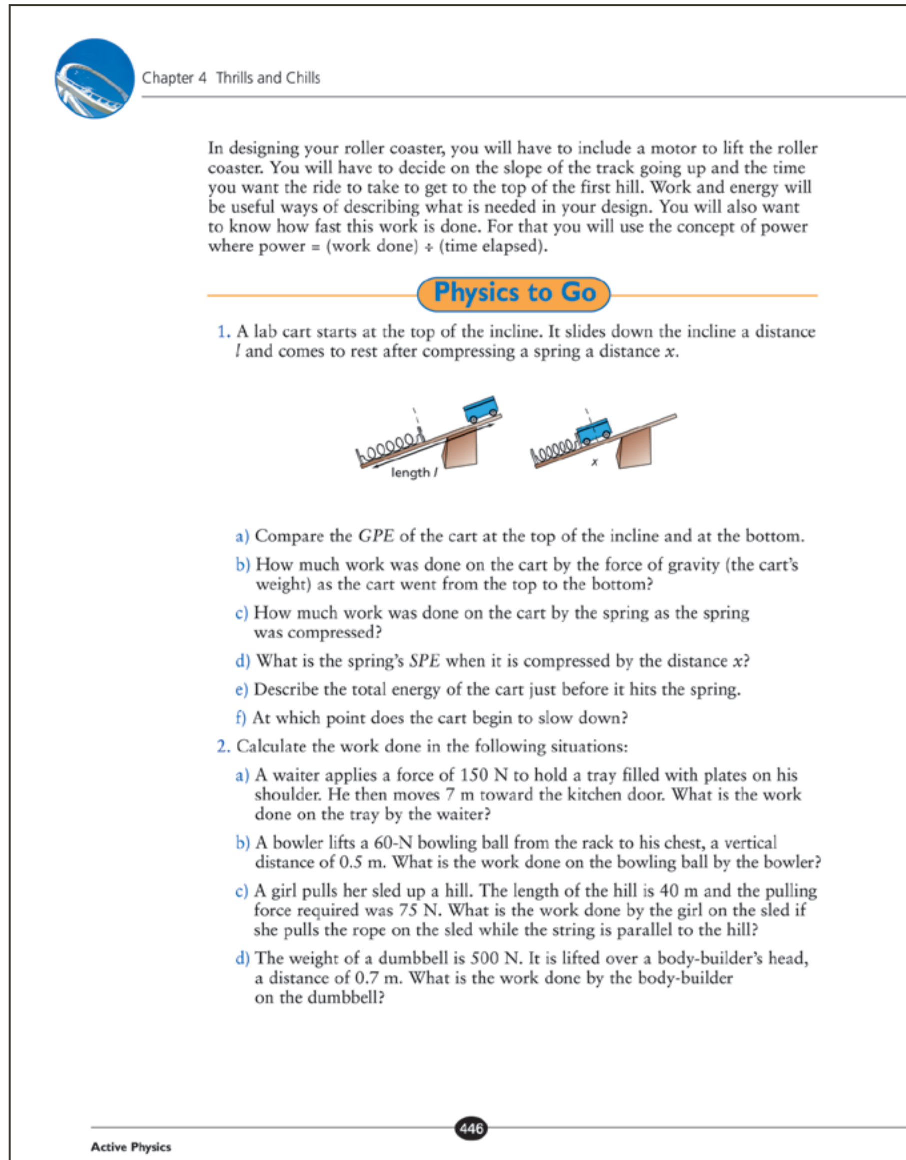
1.c)
The work by the spring $= \frac{1}{2}kx^2$

1.d)
$SPE = \frac{1}{2}kx^2$

1.e)
Before hitting the spring, the cart has some *GPE*, no *SPE*, and some *KE*.

1.f)
The cart begins to slow down when the force on the spring is greater than the force of gravity pulling the cart down the ramp. It is not when the cart first hits the spring because at that moment it is still gaining *KE*, but the spring is not yet applying a force. When the cart hits the spring, the net force on the cart along the track will start to decrease; so its acceleration will decrease, but the velocity will not decrease until the net force points up the ramp—the spring must be compressed sufficiently for that to happen.

2.a)
The waiter does no work on the tray, because the force is up and the displacement is horizontal. (The force and displacement are perpendicular.)



Chapter 4 Thrills and Chills

In designing your roller coaster, you will have to include a motor to lift the roller coaster. You will have to decide on the slope of the track going up and the time you want the ride to take to get to the top of the first hill. Work and energy will be useful ways of describing what is needed in your design. You will also want to know how fast this work is done. For that you will use the concept of power where power = (work done) ÷ (time elapsed).

Physics to Go

1. A lab cart starts at the top of the incline. It slides down the incline a distance *l* and comes to rest after compressing a spring a distance *x*.

a) Compare the *GPE* of the cart at the top of the incline and at the bottom.
b) How much work was done on the cart by the force of gravity (the cart's weight) as the cart went from the top to the bottom?
c) How much work was done on the cart by the spring as the spring was compressed?
d) What is the spring's *SPE* when it is compressed by the distance *x*?
e) Describe the total energy of the cart just before it hits the spring.
f) At which point does the cart begin to slow down?

2. Calculate the work done in the following situations:
a) A waiter applies a force of 150 N to hold a tray filled with plates on his shoulder. He then moves 7 m toward the kitchen door. What is the work done on the tray by the waiter?
b) A bowler lifts a 60-N bowling ball from the rack to his chest, a vertical distance of 0.5 m. What is the work done on the bowling ball by the bowler?
c) A girl pulls her sled up a hill. The length of the hill is 40 m and the pulling force required was 75 N. What is the work done by the girl on the sled if she pulls the rope on the sled while the string is parallel to the hill?
d) The weight of a dumbbell is 500 N. It is lifted over a body-builder's head, a distance of 0.7 m. What is the work done by the body-builder on the dumbbell?

446 Active Physics

2.b)
Given:
$F = 60$ N; $d = 0.5$ m

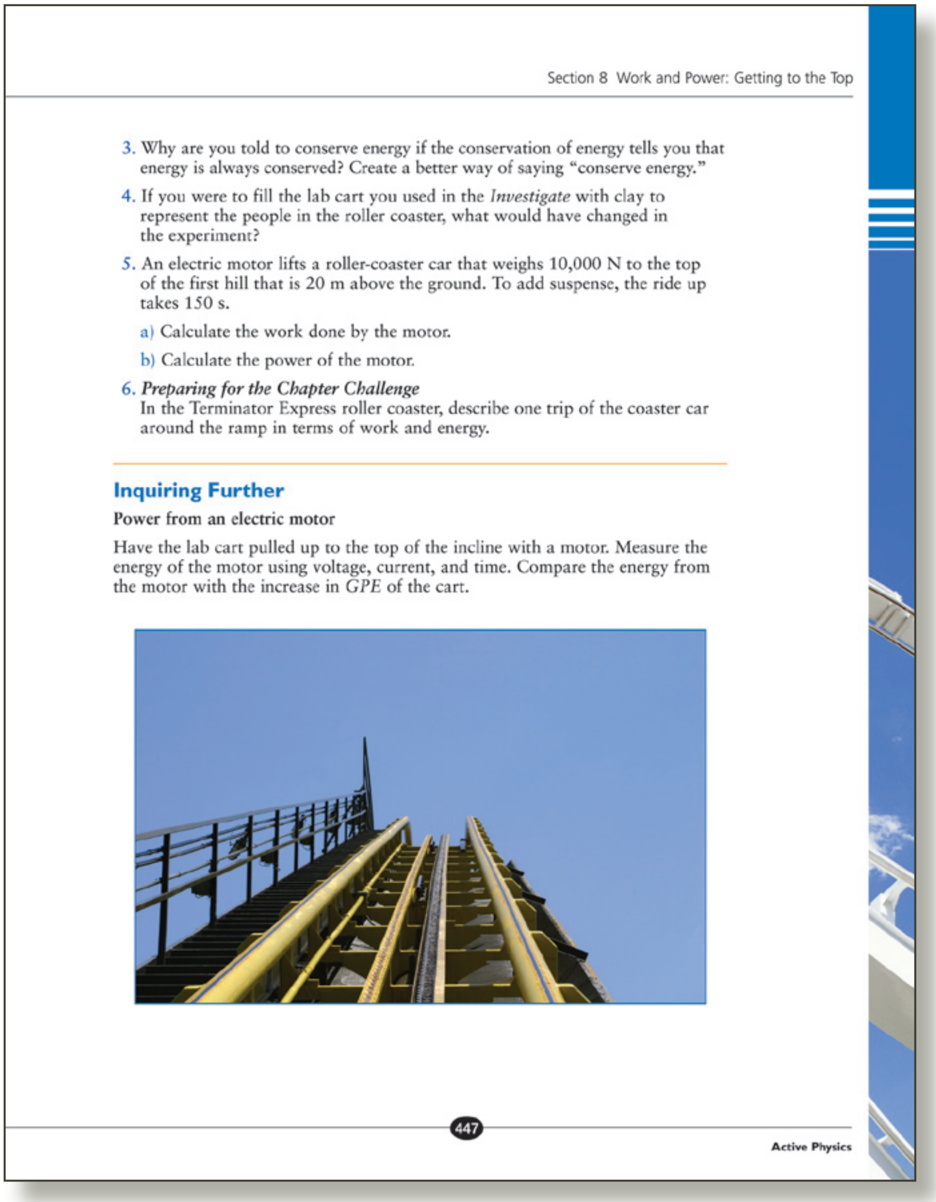
$W = F_{\parallel}d = mgh =$
$(60 \text{ N})(0.5 \text{ m}) = 30 \text{ J}$

2.c)
Given:
$F = 75$ N; $d = 40$ m

$W = F_{\parallel}d = mgh =$
$(75 \text{ N})(40 \text{ m}) = 3000 \text{ J}$

2.d)
Given:
$F = 500$ N; $d = 0.7$ m

$W = F_{\parallel}d = mgh =$
$(500 \text{ N})(0.7 \text{ m}) = 350 \text{ J}$



3. Why are you told to conserve energy if the conservation of energy tells you that energy is always conserved? Create a better way of saying "conserve energy."
4. If you were to fill the lab cart you used in the *Investigate* with clay to represent the people in the roller coaster, what would have changed in the experiment?
5. An electric motor lifts a roller-coaster car that weighs 10,000 N to the top of the first hill that is 20 m above the ground. To add suspense, the ride up takes 150 s.
   a) Calculate the work done by the motor.
   b) Calculate the power of the motor.
6. *Preparing for the Chapter Challenge*
   In the Terminator Express roller coaster, describe one trip of the coaster car around the ramp in terms of work and energy.

Inquiring Further

Power from an electric motor

Have the lab cart pulled up to the top of the incline with a motor. Measure the energy of the motor using voltage, current, and time. Compare the energy from the motor with the increase in *GPE* of the cart.

CHAPTER 4

3.

Conserve energy implies "don't waste energy," or don't use energy in excess.

4.

The force to lift the cart up the incline would have changed, so the total work would have changed. The cart's gravitational potential energy at the top of the ramp would be larger. The work in all trials would have been equal to each other.

5.a)

Given: $F = 10{,}000$ N; $d = 20$ m;

$$W = F_{\parallel} d = mgh =$$
$$= (10{,}000\ \text{N})(20\ \text{m}) = 200{,}000\ \text{J}$$

5.b)

Given: $\Delta t = 150$ s

$$P = W/\Delta t =$$
$$200{,}000\ \text{J}/150\ \text{s} = 1333\ \text{watt}$$

6.

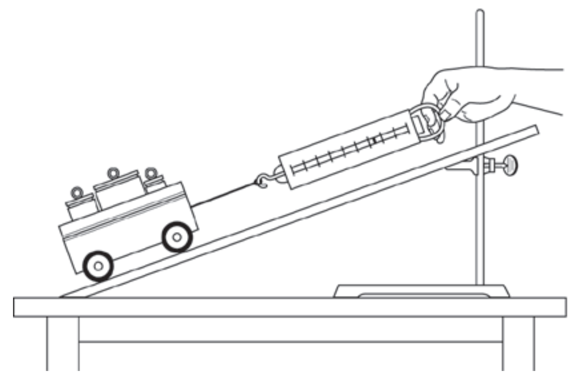
Preparing for the Chapter Challenge

The motor does positive work on the roller coaster to bring it to its highest point. As the coaster car goes down the hill, gravity does work to increase its kinetic energy until it reaches the bottom of the hill. At this point, gravity does negative work by decreasing the kinetic energy and increasing the gravitational potential energy, as the car goes up the next hill. The energy of the roller coaster is increased as the motor lifts the coaster to the top of the first hill. At all other points of the roller coaster, the total mechanical energy remains the same, if you ignore losses due to friction.

SECTION 8 QUIZ

4-8c **Blackline Master**

1. A student pulls a laboratory cart up an inclined plane with a spring scale as shown in the diagram. If the scale reads 5.6 N, and the student pulls the cart a distance of 1.4 m, how much work does she do pulling the cart?



   a) 56 J
   b) 8.0 J
   c) 7.8 J
   d) 4.0 J

2. A student who weighs 560 N climbs a flight of stairs that is 4 m high in 8 s. How much power does the student need to do this?

   a) 280 W
   b) 1120 W
   c) 5600 W
   d) 17,920 W

3. An object has a mass of 8 kg. A 2.0-N force moves the mass at constant speed 3 m east, and then 4 m back west. How much work is done moving the block?

   a) 2 J
   b) 14 J
   c) 1.75 J
   d) 112 J

4. To lift a roller-coaster car from rest at the bottom to rest at the top of the first hill, a force of 560 N acting parallel to hill is used. If the length of the incline is 80 m, what is the car's increase in gravitational potential energy?

   a) 7 J
   b) 5600 J
   c) 44,800 J
   d) 450,000 J

5. A motor has a power output of 1000 W. Using this power, how much time will it take the motor to raise a 50-N weight 100 m?

   a) 5 s
   b) 10 s
   c) 50 s
   d) 100 s

SECTION 8 QUIZ ANSWERS

1. c) The work done pulling the cart up the plane can be found using the equation $W = F \cdot d$. Solving for the work gives $W = (5.6 \text{ N})(1.4 \text{ m}) = 7.8 \text{ J}$

2. a) The power needed to climb the stairs in this time can be found from the equation $P = W/t$, where the work is found using $W = F \cdot d$. The work done is equal to the student's weight times the height the weight is lifted, or $W = (560 \text{ N})(4 \text{ m}) = 2240 \text{ J}$. The power is this work divided by the time or $P = (2240 \text{ J})/(8 \text{ s}) = 280 \text{ W}$.

3. b) The work done is found using the formula $W = F \cdot d$, where the distance is the total distance moved (not the displacement) where the force acts. Solving for the work gives $W = (2 \text{ N})(7 \text{ m}) = 14 \text{ J}$. The size of the mass is not important as long as it can be moved by a force of 2 N.

4. c) By conservation of energy, the work done raising the coaster car is going into increasing the cars *GPE*. To calculate the work use $W = F \cdot d$ Solving for the work gives $W = (560 \text{ N})(80 \text{ m}) = 44{,}800 \text{ J}$, which is the increase in *GPE*.

5. a) Using the formula for power, Power = W/t, and substituting $F \cdot d$ for work gives the equation $P = F \cdot d/t$. Inserting the given values and solving for the time gives $1000 \text{ W} = (50 \text{ N})(100 \text{ m})/t$ or $t = 5 \text{ s}$.