NYC Companion Lesson

Water Wheel Design

Overview

This hands-on activity builds on and reinforces students' understanding of how applying a force against the force of gravity can convert kinetic energy to potential energy. Students are challenged to design and build a water wheel that can lift a washer hanging from a string, storing the energy of falling water. Students determine which group's washer had the greatest change of energy, and therefore which stored the most energy, by measuring the distance the hanging washers were moved by the turning of the water wheel. Students are then introduced to the concept of work and evaluate which water wheel did the most work on the washer by thinking about which group's washer had the greatest change in energy. The purpose of this lesson is to extend students' understanding of energy with the introduction of the concept of work.

Recommended Placement: *Magnetic Fields*, after Lesson 2.2
Suggested Time Frame: 90 minutes (can be spread across multiple class periods)

NYS P–12 Science Learning Standards

Performance Expectations

- **MS-PS3-2:** Develop a model to describe that when the arrangement of objects interacting at a distance changes, different amounts of potential energy are stored in the system.
- **MS-PS3-5:** Construct, use, and present an argument to support the claim that when work is done on or by a system, the energy of the system changes as energy is transferred to or from the system.

Disciplinary Core Ideas

- **PS3.A: Definitions of Energy:**
  - A system of objects may also contain stored (potential) energy, depending on their relative positions. (MS-PS3-2)
- **PS3.B: Conservation of Energy and Energy Transfer:**
  - When the motion energy of an object changes, there is inevitably some other change in energy at the same time. (MS-PS3-5)

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Disciplinary Core Ideas	• **PS3.C: Relationship Between Energy and Forces:** ◦ When two objects interact, each one exerts a force on the other that can cause energy to be transferred to or from the object. (MS-PS3-2)
Science and Engineering Practices	• **Practice 3:** Planning and Carrying Out Investigations • **Practice 4:** Analyzing and Interpreting Data • **Practice 5:** Analyzing Data • **Practice 6:** Constructing Explanations and Designing Solutions
Crosscutting Concepts	• Cause and Effect • Energy and Matter

Vocabulary

- force
- kinetic energy
- potential energy
- work

Materials & Preparation

Materials

For the Class

- Water Wheel Design copymaster
- masking tape
- 1 single-use plastic water bottle (16 oz.)*
- utility knife
- string (2 feet)
- 1 washer (1-inch)
- 1 wooden dowel (12-inch)
- 4 dish tubs
- 4 measuring cups (2-cup)
- 4 pitchers
- paper towels*
- 4 metersticks*
- water*
- 1 large index card*
- marker*

For Each Group of Four Students

- 1 tray*
- 1 single-use plastic water bottle (16 oz.)*
- string (2 feet)
- 1 washer (1-inch)
- 1 wooden dowel (12-inch)
- masking tape

Materials (continued)

- 4 plastic cups (8 oz.)
- 8 plastic cups (2 oz.)
- 1 foil pie tin
- 6 plastic spoons
- 1 pair of scissors*
- optional: other materials as available*

For Each Student

- Water Wheel Design student sheets*

*teacher provided

Preparation

Safety Note: Sharp Objects in This Lesson

Use caution when cutting holes in the bottom of the water bottles. Never make cuts toward your hand. Make sure you are cutting on a cutting board or other surface that can withstand scratches. Wear safety goggles in case shards fly off the bottle as you cut. You may want to gather more bottles than you need so you can practice making cuts.

Before passing out wooden dowels to students, remind students how to behave when they are using materials with a sharp end.

1. **Print Water Wheel Design copymaster.** Locate the Water Wheel Design copymaster on the New York City Resources webpage: www.amplify.com/amplify-science-new-york-city-resources. Make one copy of all pages for each student.
2. **Create and post vocabulary card on the classroom wall.** With a marker, write "work" in large print on a large index card. Post this card on the classroom wall.
3. **Cut the water bottles.** With a box cutter or other sharp blade carefully cut a roughly 1-inch square hole in the bottom of each water bottle, as shown in the Teacher Reference for this lesson.
4. **Attach one washer to each water bottle.** Cut one 2-foot piece of string per group. Tie a washer to one end of each piece of string. Tape the other end of the string on the neck of the bottle below the thread, as shown in the Teacher Reference for this lesson.
5. **Set aside one prepared water bottle (with hole cut out and washer attached) and dowel for use during the lesson.**
6. **Prepare the trays.** Place 1 prepared water bottle, 1 wooden dowel, 4 large plastic cups (8 oz.), 8 small plastic cups (2 oz.), 1 foil pie tin, 6 plastic spoons, 1 pair of scissors, masking tape, and any additional materials

you have decided to provide on a tray for each group of 4 students.

7. **Prepare testing stations.** Find four places around the classroom where groups can test their water wheels as they are designing them. At each station, place a pitcher full of water, a 2-cup measuring cup, paper towels, and a dish tub. Tape a meterstick next to the dish tub with the 0 cm mark toward the floor so that students can measure the height of their washer. You may want to put a towel on the floor to catch any spilled water. Decide if you will allow students to pour the water back from the dish tubs into the pitchers or if you prefer to do that yourself. There is an example of how to test a water wheel design in the Teacher Reference for this lesson.

8. **Prepare to show students images of water wheels.** In order to support students in designing their water wheels, find images or videos showing real-world water wheels and be prepared to project them. If you have additional time, consider having students research design ideas themselves.

9. **Locate and review the Rubrics for Assessing Students' Investigations of Energy and Work in the Assessment section of this lesson.** These rubrics can help you plan to support students as they complete their design plans and draw conclusions during the lesson. After the lesson, use the rubrics to formatively assess students' developing facility with Science and Engineering Practices as well as their understanding of Disciplinary Core Ideas.

10. **Immediately before the lesson have on hand the following materials:**
    - student sheets
    - prepared trays
    - prepared water bottle and dowel for teacher demo
    - materials for testing station

Notes

Materials for This Lesson

- Consider asking students to bring in empty water bottles for this activity. They should be small enough to fit on a 12-inch wooden dowel with room for someone to hold one end of the dowel. Thinner bottles are lighter and easier to make turn and it is easier to safely cut a hole in with a box cutter. If you choose to use thicker bottles, like soda bottles, you can use a drill to make a hole in the bottom. The hole should be large enough for the bottle to turn freely on the dowel.
- To give students more design options, you may give students additional materials or ask students to bring in materials.
- The materials list and preparation steps provide enough materials for one class. You will need to make a plan to reset the trays between classes. The wooden dowels and masking tape can be reused from class to class, but other materials will need to be restocked depending on what students use. If you break this lesson into multiple class periods, you will need a place for groups to store their water wheels between classes.

Science Background

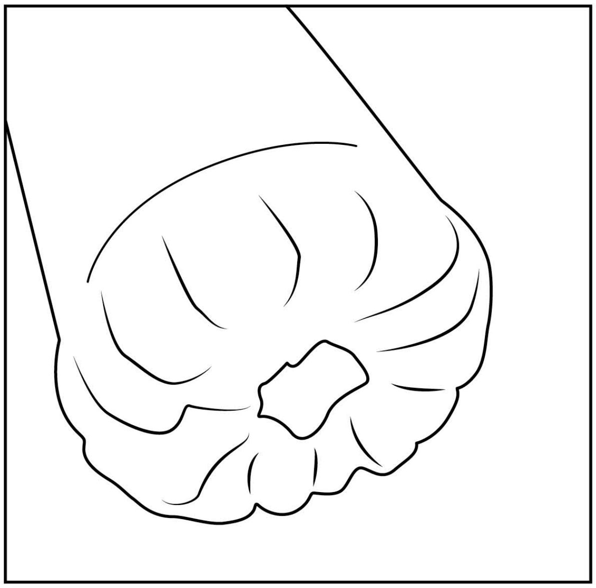
Work is a helpful concept in physics, as it provides a means for thinking about the connection between force and energy. To change an object's motion, a force must be applied. When you kick a ball, it rolls across the floor. Your foot exerted a force and the ball moved. When a force is applied to an object and that object moves, there is a transfer of energy. When you kick a ball, the kinetic energy of your foot is transferred to the ball. When the ball is moving, it has kinetic energy. *Work is a measure of the energy that is transferred when a force is applied to an object and that object moves some distance.* If a force is applied to an object and the object does not move, no work was done.

In this activity, students design a water wheel that can wind up a washer hanging from a string, storing the energy of falling water. There is an example water wheel design students could create in the Teacher Reference for this lesson. The falling water has kinetic energy that is transferred to the water wheel, making it move, winding up a washer to some height, and converting that kinetic energy to potential energy. The falling water does work on the water wheel and the water wheel does work on the washer, as evidenced by the movement of the water wheel and the movement of the washer. The more energy that is transferred to the water wheel, the more work is done on it. As the water wheel spins, energy is transferred to the washer, lifting the washer. The distance the washer travels is correlated with the change in energy of the washer, or its potential energy, so students can figure out which washer had the most work done on it by measuring which washer had the greatest change in height.

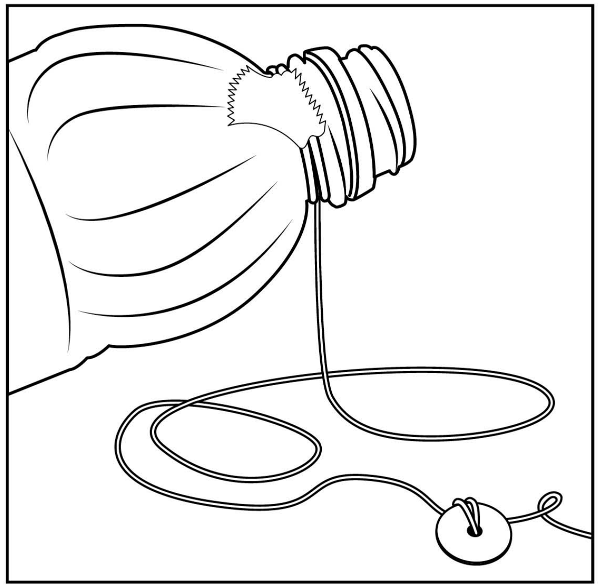
This lesson does not require students to calculate work, but it can easily be extended to incorporate this. If a constant force is applied to an object, work is calculated by multiplying the force times the distance traveled ($w = f \cdot d$). Force equals mass times acceleration ($f = m \cdot a$), so the force applied to the washer equals the mass of the washer multiplied by 9.8 m/s (the acceleration of gravity). The work done on the washer can then be calculated by multiplying the force by the distance the washer traveled (in meters).

When thinking about the work done on a system, it is often necessary to think about the scale of the object the work is being done on, and what counts as movement. For example, when you push on a wall, if the wall does not move at a macroscale, you would consider that no work was done on the wall. However, at an atomic scale, some energy would be transferred to the atoms or molecules that make up the wall and they would move a small amount. Even though no work was done on the wall as a whole, work was done on individual atoms or molecules that make up the wall.

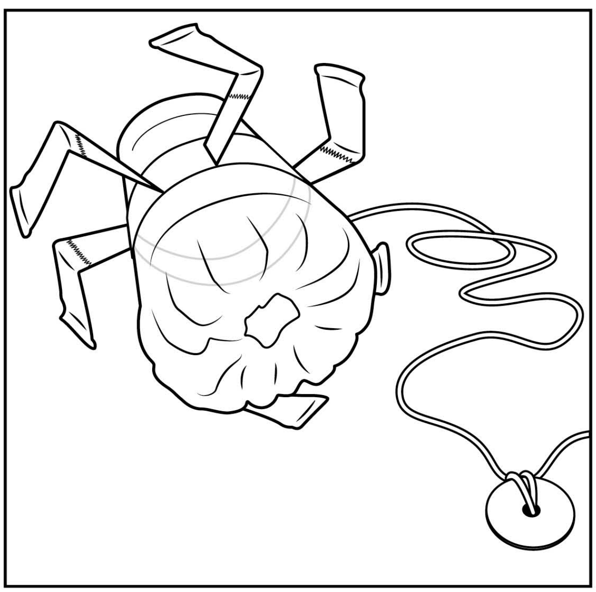
Teacher Reference



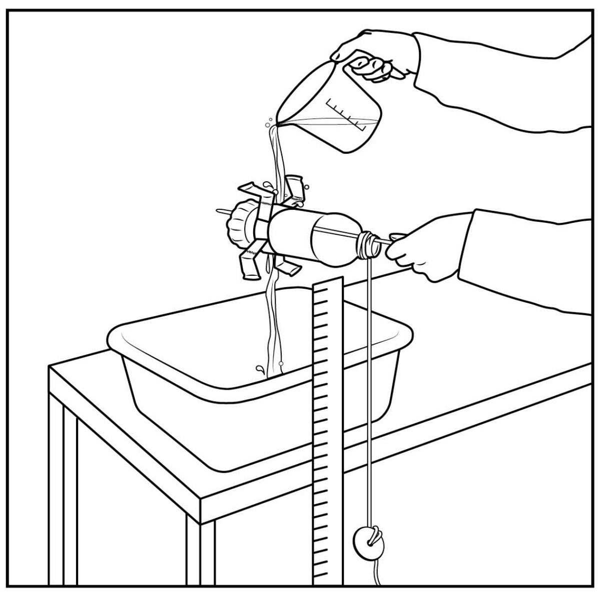
A hole cut in the bottom of a water bottle.



The string taped to the groove near cap end.



An example water wheel design.



Testing a water wheel design.

Instructional Guide

Explore and Activate Prior Knowledge

1. **Discuss the energy of water.**
   - Hold up a measuring cup filled with water above a dish bin. Ask students if the water has energy. [It has potential energy.]
   - From a distance of about 6 inches, pour the water into the dish bin. Ask students what is happening to the potential energy of the water. [As the water falls, the potential energy is being converted to kinetic energy.]
2. **Introduce the challenge.** Explain that students will be building a system that can store the energy of falling water.
3. **Invite students to share initial ideas.** Ask students to brainstorm ways that they could store the energy of falling water. Accept all ideas.
4. **Introduce water wheels.** Show the students images of real-world water wheels. Explain that these devices help convert the kinetic energy of moving water into other forms.
5. **Introduce the materials.** Hold up a wooden dowel inserted through a prepared water bottle. Explain that their challenge will be to add materials to the bottle so that when water is poured on it, the bottle turns and lifts up the washer. Their design criterion, or the way their water wheel will be judged, is that it should change the height of the washer at least 20 cm and go even higher if possible. Rotate the bottle with your hand to demonstrate the string being wound up and the washer lifting.
6. **Discuss the energy of the washer.** Ask students what will happen to the energy of the washer when it is lifted up by the water wheel. [The washer will have kinetic energy as it moves, which will be converted into potential energy as the washer gets higher up.] Explain that the water wheel they design will be a way to store energy.
7. **Pass out trays of materials.** Explain that students can cut the materials as needed. Make sure students know that they will only get one bottle, so they should be careful about modifying or cutting the bottle.
8. **Groups brainstorm.** With their group, have students begin to brainstorm how they will design their water wheel to lift the washer. Ask students to discuss and brainstorm for 5–10 minutes without modifying any of the materials or constructing anything. If you have time, you may want to have students sketch their ideas either individually or as a group.

Construct New Ideas

9. **Introduce the testing stations.** Point out the areas around the room where student groups will take turns testing their water wheels. Demonstrate how students will test them by holding a wooden dowel with a prepared bottle on it directly over a dish tub with the string and washer on the outside of the dish tub hanging toward the ground (as shown in the Teacher Reference for this lesson). Explain that for each test, students should use the pitcher to pour 500 mL of water into the measuring cup and then they should use the measuring cup to pour the water from a height of no more than 15 cm (about 6 inches) above the water wheel. Students should perform multiple tests. Let students know that they will test their final designs in front of the class.
10. **Describe how to measure the height of the washer.** Point out the meterstick and explain that students should note the initial height of the washer and subtract the initial height of the washer from the final height. Remind students that they are trying to get the washer to travel up at least 20 cm.
11. **Give students about 30 minutes to design and test their water wheels.** Circulate, giving assistance as needed. Encourage students to test their designs at the testing stations and then return to their tables to make adjustments.
12. **Discuss the energy of the water wheel.** Ask student pairs to discuss what happened to the kinetic energy of the flowing water when they poured it on their water wheel. Have students share with the class and ask them for their evidence. [The kinetic energy of the water was transferred to the water wheel. The evidence is that the water wheel moved. If their water wheel was able to lift the washer, some of the kinetic energy of the water wheel was converted into the potential energy of the washer. The evidence is that the washer was moved up, so potential energy of the washer must have increased.]
13. **Discuss potential energy.** Remind students that gravity is a force that pulls the washer down.

    As the water wheel pulls the washer up against gravity, potential energy is stored in the gravitational field between Earth and the washer. By using the water wheel, you are storing the energy of the falling water, which can be used later. The higher the washer moves, the greater the change in potential energy and the more energy is stored.

    Explain that as groups test their system, the class will also be considering which washer had the greatest increase in potential energy and therefore stored the most energy.
14. **Distribute Water Wheel Design student sheets.** Direct students to complete Part 1: Preparing to Record Data, in order to prepare them to record their data.
15. **Students create a data table.** Review Part 1 and support students, as needed, to create a data table in Part 2: Recording and Analyzing Data from Water Wheel Tests that will allow them to record class data for the change in height of the washers.

16. **Students test their water wheel designs in front of the class.** Give each group three attempts to lift the washer 20 cm. For each attempt they are allowed to pour only 500 mLs of water. Have a student measure the change of height of the washer and have the students record the results in their data tables. Remind each group to measure and note the height of the washer before each pour to get an accurate measurement.
17. **Students complete questions from Part 2.** After all groups have tested their water wheels, have students discuss and respond to questions in Part 2. Then, discuss the questions as a class.
18. **Introduce the concept of work.** Explain that the concept of work helps physicists understand the amount of energy that is transferred when a force is applied to an object and that object moves. If a force is applied to an object and that object moves, energy was transferred to that object and work was done. If the object does not move, no energy was transferred and no work was done. The more energy that is transferred to a system, the more work is done on that system.

    Work is a measure of the energy that is transferred when a force is applied to an object and that object moves some distance.

    Point out that the vocabulary word is posted on the classroom wall. Students can also find the definition in the glossary at the back of their Student Editions.
19. **Discuss work.** Ask student pairs to discuss which group's washer had the most work done to it. Ask students to share their ideas with the class. [The washer that had the greatest change in height had the most energy transferred to it and had the most work done on it.]
20. **Demonstrate a water wheel that does not lift the washer.** Hold a wooden dowel with an unmodified, prepared water bottle attached over a dish bin. Pour water over the water bottle. Ask students to discuss with a partner if any work was done on the washer. Ask students to share their ideas with the class. [Since the washer did not move, no work was done on it.]
21. **Demonstrate pushing on a wall.** Push on a solid wall. Ask student pairs to discuss the following and share their responses with the class.
    - Is pushing on a wall applying a force? [Yes.]
    - If the wall does not move, is any energy being transferred to it? [If the wall does not move, no energy is being transferred to it.]
    - If the wall does not move, is any work being done on the wall? [If the wall does not move, no work is being done to it.]

    Clarify as needed that even though you applied a force to the wall, no energy was transferred and no work was done if the wall did not move.

22. **Summarize the connection between energy and work.**

    When a force is applied to a system and that system moves some amount, work has been done on that system. If that system moves, energy must have been transferred to it. If a force is applied and the system does not move, no energy has been transferred so no work was done.

Apply New Ideas

23. **Direct students to Part 3: Applying Ideas.** Give students a few minutes to discuss the questions with a partner and write their responses.
24. **Discuss students' responses as needed.**

Rubrics for Assessing Students' Investigations of Energy and Work

The rubrics below may be used to review students' design plans and conclusions to formatively assess students' developing facility with Science and Engineering Practices and understanding of Disciplinary Core Ideas.

Rubric 1: Assessing Students' Performance of the Practice of Planning and Conducting Investigations

Note that this rubric applies to Parts 1 and 2 of the Water Wheel Design student sheets. Rubric 1 is designed to monitor and support students as they develop dexterity with the practice of Planning and Conducting Investigations. For each criterion, levels are described to monitor students' progress by indicating the degree to which students can independently demonstrate fluency with the science practice. This rubric may be used formatively to support students' facility with the practice of Planning and Conducting Investigations. It features targeted questions a teacher may use to assess students' design plans and provides specific feedback for revisions and for future encounters with the practice.

Rubric 1: Assessing Students' Performance of the Practice of Planning and Conducting Investigations		
Criteria	**Description and possible feedback**	**Level**
Produces data that can serve as the basis for evidence. Could the data generated by the investigation be used as evidence to evaluate a design solution?	Students don't specify what data will be collected. Possible feedback: *What information will you be able to record as you conduct your investigation?*	0
	Students specify the data that will be collected, but the data indicated could not serve as evidence to evaluate their design solution and the design solutions of the class. Example: We will record how fast the water wheel spins. Possible feedback: *How will your data help you to know if you met the design criterion, or which group's washer had the greatest increase in potential energy?*	1

(Table continues on the next page.)

Rubric 1: Assessing Students' Performance of the Practice of Planning and Conducting Investigations (continued)		
Criteria	**Description and possible feedback**	**Level**
(continued from previous page)	Students specify the data that will be collected, and the data indicated could serve as evidence to evaluate design solutions. Example: We need to record the change in height of our washer. We need to record the change in height of all the groups' washers.	2
Records data in a way that will be useful for analysis. Is the data table organized by independent and dependent variable?	Data table doesn't include table headers that indicate what data is being recorded or data in the table wasn't consistently categorized. Possible feedback: *What information are you recording in each column? How will you remember what the information in each box means?*	0
	Data table includes table headers and data is consistently recorded, but data is not organized by dependent and independent variables. Example: Table headers include the height the water was dropped from and the number of times the wheel spun. Possible feedback: *How would you use your data to show whether or not your system met the design criterion or to show which system stored the most energy? How could you organize your table so that information is clear?*	1
	Data table includes table headers, data is consistently recorded, and data is organized by dependent and independent variables. Example: Table headers include a way to identify which group's water wheel design is tested and the distance each group's washer moved.	2

Rubric 2: Assessing Students' Understanding of Science Ideas Encountered in the Unit

Note that this rubric applies to Part 3 of the Water Wheel Design student sheets. Rubric 2 considers whether students have constructed and applied ideas in a way that is consistent with accepted science ideas. This rubric is designed to be formative, and space is provided to note if students are demonstrating understanding or are struggling with each idea. If students are having difficulty with a particular idea or with multiple ideas, you may consider returning to the data they collected from their water wheel tests and leading a focused student discussion about how their washers changed after pouring the water on the water wheel in order to help all students build ideas about the change of energy in a system and about work.

Rubric 2: Assessing Students' Understanding of Science Ideas Encountered in the Unit		
Criteria	**Description**	**Is there evidence of student understanding?**
Consistent with accepted science ideas. Are students' conclusions consistent with accepted science ideas?	Students demonstrate understanding of the idea that the energy of a system changes as energy is transferred to or from the system. Example: Ray and Lana were able to change the energy of the box, but not Celia. I think this because Ray and Lana were able to move the box up the hill which is evidence that potential energy increased.	
	Students demonstrate understanding of the idea that work is the measure of the energy transferred when force is applied to an object and that object moves some distance. Example: Ray and Lana were able to do work on the box, but not Celia. I think this because both Ray and Lana exerted a force on the box causing the box to move.	

Water Wheel Design

Part 1: Preparing to Record Data

1. What is your design criterion?

We want to get the washer to lift at least 20 cm.

2. How will you be able to tell which group's washer had the greatest increase in potential energy (stored the most energy)?

Whichever group's washer goes the highest is the one that had the greatest increase in potential energy.

3. What data do you need to record to determine if your water wheel meets the design criterion?

We need to record the change in height of our washer.

4. What data do you need to record to determine which group's washer had the greatest increase in potential energy (stored the most energy)?

We need to record the change in height of all the groups' washers.

Possible Student Responses

Water Wheel Design (continued)

Part 2: Recording and Analyzing Data from Water Wheel Tests

Create a table to record data that will help you determine:

- whether or not your water wheel met the design criterion.
- which group's washer had the greatest increase in potential energy.

Water wheel	How far the washer was lifted
Group 1	18 cm
Group 2 (our group)	22 cm
Group 3	30 cm
Group 4	40 cm
Group 5	0 cm
Group 6	30 cm
Group 7	5 cm
Group 8	13 cm
Group 9	25 cm
Group 10	34 cm

5. Did your team's water wheel meet the design criterion? What is your evidence?

Our team's water wheel did meet the design criterion. We needed to lift the washer at least 20 cm and we lifted it 22 cm.

Water Wheel Design (continued)

6. Where did the energy come from that eventually led to the washer being lifted?

The energy to lift the washer was from the water. The kinetic energy of the water was transferred to the water wheel making it move and lifting the washer.

7. Which group's washer had the greatest increase in potential energy? How can you tell?

Group 4's washer had the greatest increase in potential energy. I know because it had the greatest change in height.

Possible Student Responses

Water Wheel Design (continued)

Part 3: Applying Ideas

Celia tries to push a heavy box up a hill. She pushes and pushes but the box does not move. Her brother and sister come to help her. Her brother, Ray, is able to push the box 2 meters up the hill. Her sister, Lana, is able to push the box 5 meters up the hill.

8. Who was able to change the energy of the box? Check all that are correct.

- [ ] Celia
- [x] Ray
- [x] Lana

Explain your answer.

Ray and Lana were able to change the energy of the box, but not Celia. I think this because Ray and Lana were able to move the box up the hill which is evidence that potential energy increased. Celia was not able to move the box up the hill so the potential energy did not increase.

Water Wheel Design (continued)

9. Who was able to do work on the box? Check all that are correct.

- [ ] Celia
- [x] Ray
- [x] Lana

Explain your answer.

Ray and Lana were able to do work on the box, but not Celia. I think this because both Ray and Lana exerted a force on the box causing the box to move. Celia was not able to move the box so no work was done.

10. Who was able to do the most work on the box? Check one.

- [ ] Celia
- [ ] Ray
- [x] Lana

Explain your answer.

Lana was able to do the most work on the box because she pushed it the farthest. She must have transferred more energy to the box to get it to move farther, so she did the most work on it.