

THINKING AND ACTING
LIKE A
SCIENTIST

TEACHER'S GUIDE

The Ups and Downs of a Roller Coaster

How is potential energy used to operate roller
coaster systems?

GRADES 9–12

Physical Science





The Ups and Downs of a Roller Coaster

Grade Level/Content	9–12/Physical Science
Lesson Summary	In this lesson, student groups will design a roller coaster and use it to investigate its energy and work.
Estimated Time	2, 45-minute class periods
Materials	Paper or graph paper, pencil and eraser, ruler or meter stick, tape, calculator, and, if designing optional hands-on models: foam tubing, marble, camera or smartphone to take pictures, Observation Form , Investigation Plan , journal
Secondary Resources	Interactive PBS Website on the Energy in a Roller Coaster The Physics of a Roller Coaster Physics and Engineering of a Roller Coaster
NGSS Connection	HS-PS3-1 Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known.
Learning Objectives	<ul style="list-style-type: none">• Students will design and sketch or model a roller coaster.• Students will develop a computational model to investigate energy and work in a closed system.• Students will make calculations using the model they have developed.

How is potential energy used to operate roller coaster systems?

Many students will be familiar with roller coasters and amusement park rides. How does a roller coaster work, and how much energy does it take? This investigation will encourage students to think about the physics behind these popular rides. Simply put, a roller coaster is a machine that uses gravity and inertia to send a train of cars along a winding track. The car ultimately starts with great potential energy and holds passengers as it travels along its track. It drops and winds, accelerating and decelerating, using centripetal force to thrill passengers as they go around loops, keeping them safely in their seats throughout the ride. The knowledge and technology to build roller coasters has been around since the mid-1800s. Early roller coasters were made of wood and metal and reached moderate speeds. Today, roller coasters can move much faster. Although the physics hasn't changed, engineers use computer models today to create faster rides that are still safe.

In this investigation, student groups will start by making predictions about how a roller coaster works. Students will then design and calculate energy transformations in their own roller coaster through the development of a computational model to quantify available energy within the closed system.

Investigation is based on the Van Andel Education Institute (VAEI) Instructional Model for Inquiry-Based Science.

In all investigations:



Students don't know the "answer" they are supposed to get.



Students play a driving role in determining the process for learning.



Teachers and students construct meaning together by journaling.



Students are working as hard as the teacher.

Part 1

INVESTIGATION SETUP

If students plan only to sketch their roller coaster design, the foam tubing, marble, and camera are not necessary. If they are modeling a roller coaster, encourage them to use foam pipe insulation available at hardware stores and other locations, or a similar material, along with tape and a marble or steel ball. Arrange for groups to have ample space to safely construct and test their roller coasters. Students will need the following:

- paper or graph paper
- pencil and eraser
- ruler or meter stick
- tape
- calculator
- foam tubing (optional)
- marble or other ball (optional)
- stopwatch (optional)
- camera or smartphone (optional)
- Internet access
- [Investigation Plan](#)
- [Observation Form](#)
- journal

Part 2

INVESTIGATION FACILITATION



Question

Introduce the investigation question.

How is potential energy used to operate roller coaster systems?

CURIOSITY

Have students bring in pictures of roller coasters. Start with older coasters that are simpler, such as one hill and a loop. Later, students can compare these coasters with newer ones with more features.

Note: If students do not have first-hand experience with roller coasters, show pictures or online resources that familiarize them with a typical ride.



Personal Knowledge

Students capture what they already know about the energy of a roller coaster.

- Students post their pictures of various roller coasters from popular and/or local theme parks around the classroom.
- Find out what students already know about potential energy, systems, and roller coasters, including their physical qualities.
- As students point out features of roller coasters, encourage them to think about the energy involved. For example, most coasters start with a chain and motor to move the car up the track. Once a roller coaster has reached its initial summit and begins its descent through loops, turns, and hills, often the only forces acting upon the coaster cars are gravity, friction, and air resistance.

RICH LANGUAGE

Review the terms *potential energy* (energy possessed by an object because of its position relative to others, stresses within itself, electric charge, and other factors), and *kinetic energy* (the energy of motion).



Prediction

Students communicate an expected outcome, based on prior knowledge.

Explain to student groups that they will calculate several values at various points along a roller coaster of their design. Ask them to predict how potential energy is used to operate their roller coaster design. Use the prompt: I predict _____ because _____. As part of their prediction, ask them to identify one point of greatest potential and one point of greatest kinetic energy based on roller coaster characteristics, such as vertical drops, loops, and other factors.

1
2
3

Investigation Plan

Students design a roller coaster model and identify points to calculate changes in energy.

The goal of the investigation is for students to design a roller coaster system and test it (if they have a physical model). Then, make calculations that allow them to develop a computational model describing energy transformations within their roller coaster.

- Direct students to follow the [Investigation Plan](#). If needed, clarify the process as students work through their design or post reminders on the board.
- Start by having students choose a picture of a roller coaster used in the previous section. As a group, have students analyze the coaster's characteristics before designing their own.
- Discuss the features each group should include in their coaster design. Possible features can be provided in a list or decided upon by each group. For example, each coaster could have:
 - boundaries of the closed roller coaster system
 - a minimum of one hill
 - a loop
 - at least one drop
 - an overall length that fits on the paper or can be modeled using available materials
- As a class, review the available materials to sketch and/or design a physical model of a one car (using a marble or ball) roller coaster system. Students may sketch their roller coaster design using paper or graph paper, a ruler, and calculator. Optionally, students may construct a model roller coaster using foam tubing and a marble or other ball.
- Inform them that they will need to identify five points (the beginning, end, and three points in between) along the coaster track to calculate important roller coaster details including: work done, potential energy, kinetic energy, velocity, and total energy using relevant formulas.
- To get started, encourage students to design, measure, and test a single span of a roller coaster such as a hill. After testing, allow them to continue designing the coaster with drops, loops, curves, etc.
- For groups that design a physical model, suggest making three or more measurements of each key coaster characteristic. Encourage students to take pictures of their design to label and include in their journal.
- Have students sketch or model their roller coaster, making careful measurements of the height and length, the degree of each drop, and the radius of any loops. Monitor the activity of each group, and answer any questions.

INVESTIGATION PLAN THE UPS AND DOWNS OF A ROLLER COASTER

1. Choose a picture of a roller coaster shared by members of your class. As a group, analyze the coaster's characteristics before beginning to design your own.
2. Discuss the features your group would like to include in your coaster. For example, each coaster should have:
 - a) a minimum of one hill
 - b) a loop
 - c) at least one drop
3. As a class, review the available materials to design a physical model of a one car (using a marble or ball) roller coaster system. Ensure that the overall length of your design can be modeled using available materials.
4. Identify five points (the beginning, end and three points in between) along the coaster track to calculate important roller coaster details including: work done, potential energy, kinetic energy, velocity, and total energy using relevant formulas.
5. To get started, design, measure, and test a single span of a roller coaster such as a hill. After testing, continue designing the coaster with your planned drops, loops, etc. Measure and record key characteristics of your design three or more times.
6. Take pictures of your design to label and include in your journal.

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Investigation Plan

Continued

CRITICAL THINKING

Use the [Fair Test](#) checklist to help students think critically about the investigation plan. Help them understand that a good investigation plan must include a test that is repeatable, generates quality data, and minimizes error. The more critically students think about their investigation plan, the more confident they will be in their results.

DISCOURSE

After they have completed their sketches, have groups compare notes with one another. What features did each group include? As students share their designs, they can present their work to one another in the way they feel will best show the qualities they have tested. This could include graphics, explanations, and/or demonstrations.



Observation

Students record key roller coaster characteristics.

Once designed and tested, review both parts of the [Observation Form](#).

Describe the observations required at each of the five chosen points. These observations include the following:

- Mass of the roller ball or coaster car (in grams)
- Roller coaster height at each of the five chosen points (in meters)
- Sections that require a pulley or similar mechanism to move the car to the top of a hill
- Radius of loops (in meters)

INTEGRITY

Check the designs and encourage students to record their data correctly. If the parameters they have chosen make calculations difficult, suggest ways to help them revise their observations or designs.

STUDENT CHOICE

Allow students to determine their own designs and ways to record their data.

Part 2: Key Roller Coaster Observations		
Mass of Ball / Coaster Car (g)	Height (m)	Date of Observation:
Start		
Point A		
Point B		
Point C		
End		

Observation Form

Part 3

INVESTIGATION ANALYSIS AND DEVELOPMENT OF CLAIM



Secondary Knowledge

Students use secondary sources to understand how to calculate energy in their roller coaster systems.

If needed, review definitions of terms and relevant formulas to support student calculations needed during Data Analysis.

Possible terms include the following:

Energy is the ability of a system or object to perform work. It exists in various forms such as potential, mechanical, kinetic, and thermal.

Continued

Potential energy is the energy an object has inside a force field due to its position. In the roller coaster's case, the potential energy comes from its height because Earth's gravity is acting on it. Roller coasters are able to move their passengers quickly up and down hills because the cars have a large amount of potential energy on the very first hill, which is usually higher than the succeeding ones. At the top of the hill, the cars have a lot of potential energy. As they go down a hill, they gain speed and kinetic energy. Throughout, friction and air resistance slow the car so that by the end of the ride, the car is usually moving much more slowly.

Kinetic energy is mechanical energy derived from the motion of an object.

Friction is a force which involves useful energy, such as the energy of motion of the roller coaster, being converted to mechanically useless energy such as heat or sound. Friction acts on all moving objects, and it is the reason a roller coaster car will eventually stop.

Conservation of energy is the principle that energy cannot be created or destroyed. Instead, energy is transformed between different forms, such as those above.

To complete the Data Analysis and develop a computational model for this investigation, students will need to calculate the following values.

- Gravitational Potential Energy (in Joules) = m (mass in kilograms) \times g (9.8 meters / second²) \times h (height in meters).
- Kinetic Energy (in Joules) = $\frac{1}{2} m$ (mass in kilograms) \times v (velocity in meters / second)²
- Total Energy (in Joules) = PE_1 (Potential Energy at pt. 1) + KE_1 (Kinetic Energy at pt. 1) = PE_2 (Potential Energy at pt. 2) + KE_2 (Kinetic Energy at pt. 2)
- Work Energy Theorem = $KE_{\text{initial}} + PE_{\text{initial}} + W_{\text{initial}} = KE_{\text{final}} + PE_{\text{final}}$

Determine whether to provide these formulas or have students research secondary sources to determine formulas necessary to calculate the requested values. (For example: [The Physics of a Roller Coaster](#). To save time, consider assigning groups specific formulas to research to share with and teach other groups.

Additional resources to develop students' understanding of the energy in a roller coaster, and how types of energy can be calculated or estimated in a closed system include the following:

[The Physics of a Roller Coaster](#)

[Physics and Engineering of a Roller Coaster](#)

Note: After reviewing these resources, students should gain an initial understanding of how energy works in a system in which the inputs and outputs are mostly known. They may apply these ideas to other systems, such as potential and kinetic energy in transportation systems.

PERSEVERANCE

Use this secondary knowledge during or after the investigation as appropriate. If students had success in designing a roller coaster and making some calculations, pose other problems they might pursue based on the same models. If students struggled with the design, questions, or calculations, ask them to retrace their steps through the investigation plan. This demonstrates to students the nonlinear nature of the science process, with an emphasis on successive trials and the design and redesign process.



Data Analysis

Students make sense of their data by organizing it and representing it visually.

Have students analyze their data. They may wish to use the [Data Analysis](#) prompt as a guide.

- Students should complete any necessary calculations using observed data to calculate the following at each of the five locations.
 - Potential Energy
 - Kinetic Energy
 - Total Energy
 - Velocity
 - Work done by an outside source (where applicable)
- Have students **evaluate** the trustworthiness of their data (highlight data that seems out of place).
- Ask students to **organize** their data, sorting the data into groups that will help them answer the investigation question. They may want to record data in a table or spreadsheet for easy comparison.
- Ask students to create a visual display to **represent** their data to show patterns or trends in their roller coaster design and to compare it to designs produced by other groups. Instruct students to add relevant formulas to calculate potential and kinetic energy to the sketch of their roller coaster design.
- Have students **interpret** what the identified patterns or trends mean. Then have them summarize in a few sentences the main findings from the analyzed data that can be used as evidence to support a claim. Ensure they have enough data that it can be used as evidence to support a claim.

CRITICAL THINKING

Have students decide how to organize and represent the data. Guide them as needed in determining the most effective organization and representations. Ask questions such as, “Would that be clear to someone from another team?” and “Is there anything in your representation that might be confusing?”

STUDENT CHOICE

Allow students to determine their own ways to represent their data. Representations could include showing a simplified form of their model, an animation, photos, drawings, etc.



Explanation

Students write a claim and provide evidence and reasoning to support it.

Have students use what they’ve discovered from the analyzed data to write an explanation that answers their investigation question. Students may wish to use the [Explanation](#) prompt as a guide.

- Have students write their explanation in their journal.
- Have students develop a **Claim** to answer the question: How is potential energy used to operate roller coaster systems?
- Then, have them add **Evidence** (the analyzed data) to support their claim.
- Finally, have them add **Reasoning** to their claim. Reasoning should include the information obtained from this investigation as well as science principles they have learned.

Continued

Claim

The amount of potential energy at any point of the roller coaster in Joules equals the product of the coaster car's mass, the height of the first hill of the coaster, and the acceleration due to gravity ($PE = m \times g \times h$). This potential energy is transformed into kinetic energy as the car goes downhill and is used to carry the car along the roller coaster's path.

Evidence

The total amount of energy within our coaster system is 12,500 Joules. The available energy changes back and forth from potential energy to kinetic energy as the coaster moves along the path. As the coaster moves along its path, it loses energy due to friction and may be provided with additional energy from outside the system.

Reasoning

Investigation: We designed and carefully measured the characteristics of our model roller coaster. We measured the key characteristics of our design three separate times. We also confirmed with the other groups in our class that our energy calculations were correct.

Science: We researched relevant and reputable roller coaster physics websites and discussed each of the related energy calculations required to develop our computational model.

- Once the explanation is written, have students discuss their results using a [Present and Defend](#).

DISCOURSE

Have students conduct a [Present and Defend](#) to develop presentation skills as well as audience participation. Research teams present a summary of their investigation to the class. The class analyzes the information presented and asks clarifying questions, challenges and/or supports the arguments made, and even presents alternative explanations as appropriate. Research teams defend their explanation with evidence and reasoning. If students are doing the same investigation plan, choose 1 or 2 groups to share.



Evaluation

Students reflect on the investigation.

- Ask students how confident they are in their results.
- Ask students what question they would like to explore next about energy transformations within closed systems.

Part 4

INVESTIGATION ASSESSMENT AND EXTENSION



Application

Students demonstrate understanding of how to apply computational models to other roller coasters designed by students from different classes or school years.

Share roller coaster designs from different classes or school years. Have students apply their learning by answering the questions: What are the types of energy in the provided roller coaster? How does this energy act to move the car and passengers through the ride?

Assessment

Ask students:

1. *How did the car (and passengers) in your roller coaster move through the ride? What forces were at work, and what slowed down the ride?*
2. *What are several ways you could increase and decrease the speed of the coaster? Based on your investigation and research of secondary sources, what is the steepest drop that is still safe? The tightest loop?*

Evaluate each group's explanation on how well students:

- designed and sketched or modeled a roller coaster.
- developed a computational model to investigate energy and work in a roller coaster system.
- made calculations using the model they developed.

Extensions

Now that students understand some of the fundamentals of energy in a closed system, they can use this knowledge to investigate energy in other scenarios.

INVESTIGATION PLAN

THE UPS AND DOWNS OF A ROLLER COASTER

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2. Discuss the features your group would like to include in your coaster. For example, each coaster should have:
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3. As a class, review the available materials to design a physical model of a one car (using a marble or ball) roller coaster system. Ensure that the overall length of your design can be modeled using available materials.
4. Identify five points (the beginning, end and three points in between) along the coaster track to calculate important roller coaster details including: work done, potential energy, kinetic energy, velocity, and total energy using relevant formulas.
5. To get started, design, measure, and test a single span of a roller coaster such as a hill. After testing, continue designing the coaster with your planned drops, loops, etc. Measure and record key characteristics of your design three or more times.
6. Take pictures of your design to label and include in your journal.

OBSERVATION FORM

THE UPS AND DOWNS OF A ROLLER COASTER

NAME: _____

DATE: _____

Part 1: Roller Coaster Diagram and Key Characteristics (sketch in this space or on the back)

In your diagram, label your five points (start, end and three points in between). As you continue your investigation, identify characteristics that are helpful in the development of your computational model. For example, you might record the height, calculated speed, and potential energy of the roller coaster's cars at each of your chosen points.

Part 2: Key Roller Coaster Observations

Mass of ball / coaster car (g)				Date of Observation:	
	Height (m)			Special Notes:	
Start					
Point A					
Point B					
Point C					
End					