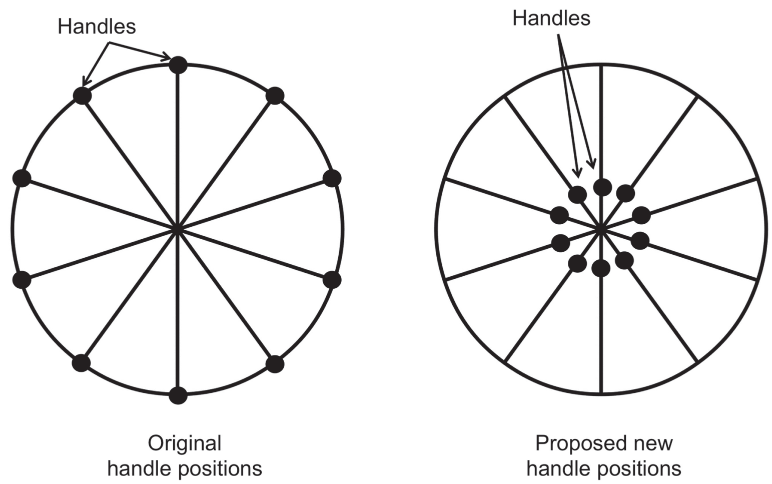
Checkout Questions

Lab 12. Torque and Rotation: How Can Someone Predict the Amount of Force Needed to Open a Bottle Cap?

1. A contestant on a game show was spinning a large wheel to try and win money. The contestant was spinning the wheel as hard as he could, but the wheel only spun around a couple of times. The contestant suggested moving the handles closer to the center so that he and other players could make the wheel spin more with each push. The suggested change is shown below.



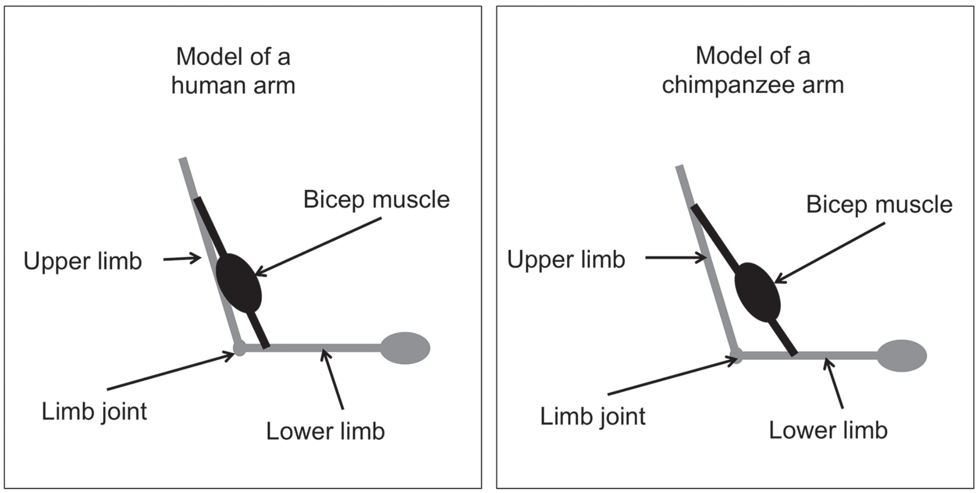
   Will moving the handles closer to the center of the wheel help the contestants get more spins per push?

   a. Yes
   b. No

   Explain your answer, using what you know about torque and rotational motion.

2. The bones and muscles found in humans and chimpanzees are almost identical. Chimpanzees, however, are much stronger than humans even though they are smaller. One explanation for this difference in strength is that the muscles of

chimpanzees are attached to the bones in slightly different ways than those of humans; therefore, chimpanzees are able to generate a greater torque with smaller muscles. The diagram below shows where the bicep muscle is attached to the upper and lower limb in a human arm and in a chimpanzee arm. When thinking about this, remember that muscles can only contract, so a bicep muscle pulls the lower limb toward the upper limb.



Use what you know about torque to explain why the difference could result in greater torque.

3. In science, it is possible for a variable to be proportionally related to two other variables.

   a. I agree with this statement.

   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about torque and the rotation of bottle caps.

4. Science requires imagination and creativity.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about torque and the rotation of bottle caps.

5. There is a difference between data and evidence in science. Explain what data and evidence are and how they are different from each other, using an example from your investigation about torque and the rotation of bottle caps.

6. In science, identifying the system under study is a prerequisite for being able to mathematically model the system. Explain why this statement is true, using an example from your investigation about torque and the rotation of bottle caps.

SECTION 5

Forces and Motion

Oscillations

Introduction Labs

Teacher Notes

Lab 13. Simple Harmonic Motion and Pendulums: What Variables Affect the Period of a Pendulum?

Purpose

The purpose of this lab is to *introduce* students to the core idea of forces and motion, part of the disciplinary core idea (DCI) of Motion and Stability: Forces and Interactions from the *NGSS,* by giving them an opportunity to explore simple harmonic motion and the behavior of pendulums. This lab also gives students an opportunity to learn about the crosscutting concepts (CCs) of (a) Patterns; (b) Cause and Effect: Mechanism and Explanation; and (c) Structure and Function from the *NGSS.* In addition, this lab can be used to help students understand two big ideas from AP Physics: (a) fields existing in space can be used to explain interactions and (b) the interactions of an object with other objects can be described by forces. As part of the explicit and reflective discussion, students will also learn about (a) the difference between data and evidence in science and (b) the nature and role of experiments in science.

Underlying Physics Concepts

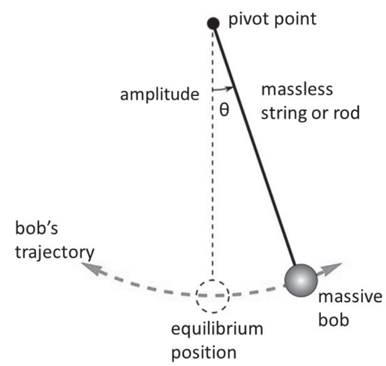
Harmonic oscillation is a concept that appears throughout physics courses because it can be easily modeled using a sine function. Furthermore, harmonic oscillators have many uses in daily life, such as in clocks, metronomes, car shock absorbers, and even some electrical devices. There are certain features that all harmonic oscillators share. First, when the system is at rest, the oscillator is said to be at "equilibrium." When the oscillator is moved from the equilibrium position, a force acts on the oscillator to restore the oscillator to equilibrium. This force is called the *restoring force.* The further the oscillator is moved from the equilibrium position, the greater the restoring force becomes.

Newton's second law states that an unbalanced force will cause an object to accelerate. Thus, when the oscillator is disturbed from equilibrium, it accelerates in the general direction of the equilibrium position. When the oscillator reaches the equilibrium position, it has a non-zero velocity, while the sum of the forces acting on the oscillator is zero. Thus, the oscillator moves through the equilibrium position, at which point the restoring force increases until it reaches a maximum displacement from the equilibrium. At the maximum displacement, the restoring force is also at a maximum, while the velocity is equal to zero (0 m/s).

In this lab, students investigate pendulums and determine what variables affect the period of the pendulum. There are three major components of a pendulum, shown in Figure 13.1: the pivot point about which the pendulum swings, the mass (called a bob) at the end of the pendulum, and a rod (or string) that connects the pivot point and the bob. When the pendulum is not moving, the mass hangs vertically at the equilibrium position. When the pendulum swings back and forth, the pendulum is displaced from the equilibrium position by an angle θ. Finally, gravity is the restoring force that causes a pendulum disturbed from equilibrium to swing back and forth. The *period of the pendulum* is defined as the amount of time that it takes the pendulum to make one full swing (we define the initial position as the release point of the pendulum when it is moved from the equilibrium position). A full swing is the mass of the pendulum returning to its initial position. In other words, a full swing is the pendulum making one full back-and-forth swing.

FIGURE 13.1

Diagram of a pendulum



The way a pendulum bob moves back and forth is described as simple harmonic motion. The motion of a pendulum bob is called *simple* because after the mass is pulled back from the equilibrium position to its initial position, the only other forces acting on the pendulum mass are the tension in the string and gravity. When friction also acts on a pendulum, the motion is called damped; if another force is exerted on the pendulum to help it keep swinging, the motion is called driven.

Students will discover that the only variable that affects the period of a pendulum is the length of string. Equation 13.1 describes the period of a pendulum, with *T* being the period of the pendulum, *L* being the length of the pendulum, and **g** being the acceleration due to gravity (9.8 m/s^2; note that for mathematical purposes, we choose to write **g** as a positive number in this lab). In SI units, period is measured in seconds (s) and the length of the pendulum is measured in meters (m). This means that the other two variables that they are likely to test—the mass at the end of the pendulum and the angle of swing—do not influence the period of the pendulum.

(Equation 13.1) $T = 2\pi\sqrt{(L/\mathbf{g})}$,

Using the law of conservation of energy, it is easy to demonstrate why the mass at the end of the pendulum does not affect the period. When the mass is pulled from equilibrium, it will also raise height **h** above the equilibrium point. The law of conservation of energy says that the gravitational potential energy at the release point will equal the kinetic energy at the equilibrium point. We can then apply Equation 13.2 to the system, where *m* is the mass, **g** is the acceleration due to gravity (9.8 m/s^2), **h** is the height above the equilibrium position, and **v** is the velocity of the pendulum bob. In SI units, mass is measured in kilograms (kg), height is measured in meters (m), and velocity is measured in meters per second (m/s).

(Equation 13.2) $m\mathbf{gh} = \frac{1}{2}m\mathbf{v}^2$

When solving for velocity, the mass on each side divides to 1, thus the velocity at the bottom is shown in Equation 13.3. Notice how for any given height, the velocity at the bottom does not depend on the mass of the pendulum bob.

$$\textbf{(Equation 13.3)} \quad \mathbf{v} = \sqrt{(2\mathbf{gh})}$$

The issue of the angle is a bit more complex. Equation 13.1 is valid when the angle of amplitude is small (see Figure 13.1). For larger angles, the amplitude will influence the period. However, this influence is small, even for relatively large angles; for example, an amplitude of 60° produces a deviation of only 7% between the true period and the predicted period. This difference is not large enough to affect the period in a meaningful way when using the suggested materials.

Timeline

The instructional time needed to complete this lab investigation is 170–230 minutes. Appendix 3 (p. 531) provides options for implementing this lab investigation over several class periods. Option C (230 minutes) should be used if students are unfamiliar with scientific writing, because this option provides extra instructional time for scaffolding the writing process. You can scaffold the writing process by modeling, providing examples, and providing hints as students write each section of the report. Option C can also be used if students are unfamiliar with any of the data collection and analysis tools. Option D (170 minutes) should be used if students are familiar with scientific writing and have developed the skills needed to write an investigation report on their own. In option D, students complete stage 6 (writing the investigation report) and stage 8 (revising the investigation report) as homework.

Materials and Preparation

The materials needed for this investigation are listed in Table 13.1. The consumables and equipment can be purchased from a science supply company such as Carolina, Flinn Scientific, PASCO, Vernier, or Ward's Science. You can also purchase many of these materials from a general retail store such as Wal-Mart or Target. Video analysis software can be purchased from Vernier (Logger *Pro*) or PASCO (SPARKvue or Capstone). These companies also have apps that can be used on Apple- or Android-based tablets and cell phones. We recommend consulting with your school's information technology coordinator to determine the best option for your students.

TABLE 13.1

Materials list for Lab 13

Item	Quantity
Consumables	
Tape	As needed
String	1 roll per group
Equipment and other materials	
Safety glasses or goggles	1 per student
Electronic or triple beam balance	1 per group
Washers	Several per group
Paper clips	5 per group
Protractor	1 per group
Ruler	1 per student
Meterstick	1 per group
Stopwatch	1 per student
Scissors	1 per group
Investigation Proposal C (optional)	3 per group
Whiteboard, 2' × 3'*	1 per group
Lab Handout	1 per student
Peer-review guide and teacher scoring rubric	1 per student
Checkout Questions	1 per student
Equipment for sensors (optional)	
Photogate and interface	1 per group
Computer, tablet, or graphing calculator with data collection and analysis software	1 per group
Equipment for video analysis (optional)	
Video camera	1 per group
Computer or tablet with video analysis software	1 per group

* As an alternative, students can use computer and presentation software such as Microsoft PowerPoint or Apple Keynote to create their arguments.

Be sure to use a set routine for distributing and collecting the materials during the lab investigation. One option is to set up the materials for each group at each group's lab station before class begins. This option works well when there is a dedicated section of the classroom for lab work and the materials are large and difficult to move (such as a dynamics track). A second option is to have all the materials on a table or cart at a central location. You can then assign a member of each group to be the "materials manager." This individual is responsible for collecting all the materials his or her group needs from the table or cart during class and for returning all the materials at the end of the class. This option works well when the materials are small and easy to move (such as stopwatches, metersticks, or hanging masses). It also makes it easy to inventory the materials at the end of the class before students leave for the day.

Safety Precautions

Remind students to follow all normal lab safety rules. In addition, tell students to take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Use caution when working with scissors. They are sharp and can cut or puncture skin.
4. Wash hands with soap and water after completing the lab.

Topics for the Explicit and Reflective Discussion

Reflecting on the Use of Core Ideas and Crosscutting Concepts During the Investigation

Teachers should begin the explicit and reflective discussion by asking students to discuss what they know about the core idea they used during the investigation. The following are some important concepts related to the core idea of forces and motion that students need to use to determine which variables do and which variables do not change the period of the pendulum:

- Force is considered a vector quantity because a force has both magnitude and direction.
- A restoring force can result in oscillatory motion.
- Simple harmonic motion occurs when a restoring force is directly proportional to the displacement of an object and acts in the direction opposite to that of displacement.
- Gravity can act as a restoring force.

To help students reflect on what they know about forces and motion, we recommend showing them two or three images using presentation software that help illustrate these important ideas. You can then ask the students the following questions to encourage them to share how they are thinking about these important concepts:

1. What do we see going on in this image?
2. Does anyone have anything else to add?
3. What might be going on that we can't see?
4. What are some things that we are not sure about here?

You can then encourage students to think about how CCs played a role in their investigation. There are at least three CCs that students need to use to determine which variables do and which variables do not change the period of the pendulum: (a) Patterns; (b) Cause and Effect: Mechanism and Explanation; and (c) Structure and Function (see Appendix 2 [p. 527] for a brief description of these CCs). To help students reflect on what they know about these CCs, we recommend asking them the following questions:

1. Why is it important to look for patterns during an investigation?
2. What patterns did you identify during your investigation? What did the identification of these patterns allow you to do?
3. Why is it important to identify causal relationships in science?
4. What did you have to do during your investigation to determine if a factor did or did not cause a change in the period of a pendulum? Why was that useful to do?
5. The way an object is shaped or structured determines many of its properties and how it functions. Why is it useful to think about the relationship between structure and function during an investigation?
6. Why was it useful to examine the structure of a pendulum when attempting to determine which variables do and which variables do not change the period of a pendulum?

You can then encourage the students to think about how they used all these different concepts to help answer the guiding question and why it is important to use these ideas to help justify their evidence for their final arguments. Be sure to remind your students to explain why they included the evidence in their arguments and make the assumptions underlying their analysis and interpretation of the data explicit in order to provide an adequate justification of their evidence.

Reflecting on Ways to Design Better Investigations

It is important for students to reflect on the strengths and weaknesses of the investigation they designed during the explicit and reflective discussion. Students should therefore be encouraged to discuss ways to eliminate potential flaws, measurement errors, or sources of uncertainty in their investigations. To help students be more reflective about the design of their investigation and what they can do to make their investigations more rigorous in the future, you can ask them the following questions:

1. What were some of the strengths of the way you planned and carried out your investigation? In other words, what made it scientific?
2. What were some of the weaknesses of the way you planned and carried out your investigation? In other words, what made it less scientific?
3. What rules can we make, as a class, to ensure that our next investigation is more scientific?

Reflecting on the Nature of Scientific Knowledge and Scientific Inquiry

This investigation can be used to illustrate two important concepts related to the nature of scientific knowledge and the nature of scientific inquiry: (a) the difference between data and evidence in science and (b) is the nature and role of experiments in science (see Appendix 2 for a brief description of these two concepts). Be sure to review these concepts during and at the end of the explicit and reflective discussion. To help students think about these concepts in relation to what they did during the lab, you can ask them the following questions:

1. You had to talk about data and evidence during your investigation. Can you give me some examples of data and evidence from your investigation?
2. Can you work with your group to come up with a rule that you can use to determine if a piece of information is data or evidence? Be ready to share in a few minutes.
3. I asked you to design and carry out an experiment as part of your investigation. Can you give me some examples of what experiments are used for in science?
4. Can you work with your group to come up with a rule that you can use to decide if an investigation is an experiment or not? Be ready to share in a few minutes.

You can also use presentation software or other techniques to encourage your students to think about these concepts. You can show examples of information from the investigation that are either data or evidence and ask students to classify each example and explain their thinking. You can also show images of different types of investigations (such as a physicist or an astronomer collecting data using a telescope as part of an observational or descriptive study, a person working in the library doing a literature review, a person working on a computer to analyze an existing data set, and an actual experiment) and ask students to indicate if they think each image represents an experiment and why or why not.

Be sure to remind your students that, to be proficient in science, it is important that they understand what counts as scientific knowledge and how that knowledge develops over time.

Hints for Implementing the Lab

- Allowing students to design their own procedures for collecting data gives students an opportunity to try, to fail, and to learn from their mistakes. However, you can scaffold students as they develop their procedure by having them fill out an investigation proposal. These proposals provide a way for you to offer students hints and suggestions without telling them how to do it. You can also check the proposals quickly during a class period. We suggest having them fill out an investigation proposal for each experiment they do. For this lab we suggest using Investigation Proposal C.
- Allow students to become familiar with the equipment and materials as part of the tool talk before they begin to design their investigation. Giving them 5–10 minutes to examine the equipment and materials allows them to see what they can and cannot do with them. This also gives students a chance to begin thinking about what variables to test and how to control for other variables.
- If you choose to have students mathematically model the relationship between the period and the length, it is important to realize that they will likely first run a linear regression and get a very high correlation coefficient for an equation of the form y = mx +b, where y corresponds to the period and x corresponds to the length of the pendulum. If this occurs, there are two ways to guide them toward a better equation. First, you can ask them to predict what the period of a pendulum with a length of 0.0 m would be. Their regression equation will give them a period greater than 0 s (because the value for b in their linear equation will be greater than zero), which is a nonsensical answer. Thus, they need an equation where the predicted period of a pendulum with length 0.0 m is 0 s. Second, you can ask them to collect data for a pendulum with a length greater than 1 m. This will provide a more pronounced data point, and the correlation coefficient will be reduced. They will then use other types of regressions and find that a power regression will give them the best model.
- If you choose to have students mathematically model the relationship between the period and the length, a power regression will give them an equation similar to $T = 2L^{½}$ or $T = 2\sqrt{(L)}$. This comes from recognizing that, first, it is possible to rewrite the full equation $T = 2\pi\sqrt{(L/\mathbf{g})}$ as $T = (2\pi/\sqrt{\mathbf{g}})(\sqrt{L})$; 2, π, and $\mathbf{g}$ are all constants. On Earth, the value of $\mathbf{g}$ is 9.8 m/s^2, so $2\pi/\sqrt{\mathbf{g}}$ resolves to be approximately 2. This is a nice opportunity for an extension, to ask students where the constant comes from in their regression equation.
- Be sure to allow students to go back and re-collect data at the end of the argumentation session. Students often realize that they made numerous mistakes when they were collecting data as a result of their discussions during the argumentation session. The students, as a result, will want a chance to re-collect data, and the re-collection of data should be encouraged when time allows.

This also offers an opportunity to discuss what scientists do when they realize a mistake is made inside the lab.

If students use a photogate

- Be sure that students record actual values (e.g., period in seconds) or save any graphs generated by a computer, rather than just attempting to hand draw what they see on the computer screen

If students use video analysis

- We suggest allowing students to familiarize themselves with the video analysis software before they finalize the procedure for the investigation, especially if they have not used such software previously. This gives students an opportunity to learn how to work with the software and to improve the quality of the video they take.
- Remind students to hold the video camera as still as possible. Any movement of the camera will introduce error into their analysis. If using actual camcorders, we recommend using a tripod to hold the camera steady. If students are using a camera on a cell phone or tablet, we recommend using a table to help steady the camera.
- Remind students to place a meterstick in the same field of view as the motion they are capturing with the video camera. Also, the meterstick should be approximately the same distance from the camera as the motion. Most video analysis software requires the user to define a scale in the video (this allows the software to establish distances and, subsequently, other variables dependent on distance and displacement).

Connections to Standards

Table 13.2 highlights how the investigation can be used to address learning objectives from AP Physics 1; learning objectives from AP Physics C: Mechanics, *Common Core State Standards,* in English language arts (*CCSS ELA*); and *Common Core State Standards,* Mathematics (*CCSS Mathematics*).

TABLE 13.2

Lab 13 alignment with standards

***NGSS* performance expectations**	• None
AP Physics 1 learning objectives	• 3.A.1.1: The student is able to express the motion of an object using narrative, mathematical, and graphical representations. • 3.A.1.2: The student is able to design an experimental investigation of the motion of an object. • 3.A.1.3: The student is able to analyze experimental data describing the motion of an object and is able to express the results of the analysis using narrative, mathematical, and graphical representations. • 3.A.3.1: The student is able to analyze a scenario and make claims (develop arguments, justify assertions) about the forces exerted on an object by other objects for different types of forces or components of forces. • 3.B.3.1: The student is able to predict which properties determine the motion of a simple harmonic oscillator and what the dependence of the motion is on those properties. • 3.B.3.2: The student is able to design a plan and collect data in order to ascertain the characteristics of the motion of a system undergoing oscillatory motion caused by a restoring force.
AP Physics C: Mechanics learning objectives	• I.F.3: Students should be able to apply their knowledge of simple harmonic motion to the case of a pendulum, so they can: • I.F.3.a: Derive the expression for the period of a simple pendulum. • I.F.3.b: Apply the expression for the period of a simple pendulum. • I.F.3.d: Analyze the motion of a torsional pendulum or physical pendulum in order to determine the period of small oscillations.
Literacy connections (*CCSS ELA*)	• *Reading:* Key ideas and details, craft and structure, integration of knowledge and ideas • *Writing:* Text types and purposes, production and distribution of writing, research to build and present knowledge, range of writing • *Speaking and listening:* Comprehension and collaboration, presentation of knowledge and ideas
Mathematics connections (*CCSS Mathematics*)	• *Mathematical practices:* Reason abstractly and quantitatively, construct viable arguments and critique the reasoning of others, use appropriate tools strategically, attend to precision • *Number and quantity:* Reason quantitatively and use units to solve problems, represent and model with vector quantities, perform operations on vectors • *Algebra:* Interpret the structure of expressions, understand solving equations as a process of reasoning and explain the reasoning, solve equations and inequalities in one variable • *Functions:* Understand the concept of a function and use function notation, interpret functions that arise in applications in terms of the context, interpret expressions for functions in terms of the situation they model • *Statistics and probability:* Summarize, represent, and interpret data on two categorical and quantitative variables; understand and evaluate random processes underlying statistical experiments; make inferences and justify conclusions from sample surveys, experiments, and observational studies

LAB 13

Lab Handout

Lab 13. Simple Harmonic Motion and Pendulums: What Variables Affect the Period of a Pendulum?

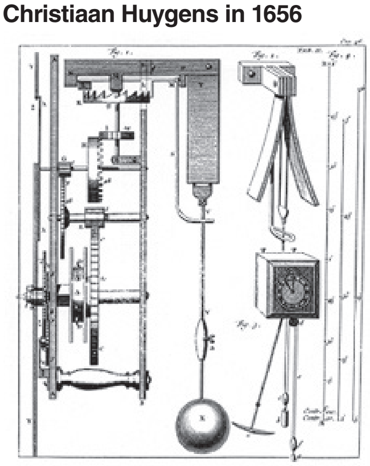
Introduction

A pendulum, which is a mass swinging at the end of a rope, has a wide range of uses in our daily lives. One of the most frequent uses of a pendulum is in a clock. Christiaan Huygens built the first pendulum clock in 1656 (see Figure L13.1 and version available at *www.nsta.org/adi-physics1*), and his use of a pendulum to keep accurate time was considered a breakthrough in clock design. Pendulums can also be found as parts of amusement park rides, in religious ceremonies, and in tools that help musicians keep a beat. Most school-age children are also familiar with pendulums, because playground swings are just a pendulum with a person at one end.

Pendulums are part of a class of objects that undergo simple harmonic motion; such objects are called oscillators. Harmonic oscillators are objects that move about a point called the equilibrium position (see Figure L13.2). When a pendulum is not moving, the bob will rest (or hang motionless) at the equilibrium position. When an outside force moves the bob from its equilibrium position, a restoring force causes the object to move back toward its equilibrium position. This process is then repeated multiple times as the bob swings back and forth. This motion is referred to as *simple,* because after the initial force to move the bob from equilibrium, the only forces acting on the bob are the restoring force and the tension in the string. Other types of harmonic motion are called *damped,* when friction slows down the motion, or *driven,* when an outside force is repeatedly exerted on the oscillator. There

FIGURE L13.1

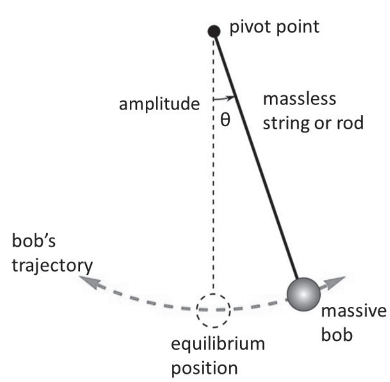
The original pendulum clock built by Christiaan Huygens in 1656



Note: This image is best viewed on the book's Extras page at *www.nsta.org/adi-physics1*.

FIGURE L13.2

The components of a pendulum



are many ways to describe the motion of a bob. The most frequent is the period (*T*), which is how long it takes a bob to make one full swing back and forth.

For most pendulums, the period does not change from one swing to the next. This makes the pendulum a particularly useful tool for timekeeping, such as in the pendulum clock shown in Figure L13.1. Early physicists recognized this and investigated the pendulum to understand what variables influence its period. This would allow them to more effectively use pendulums in clocks, as well as in other devices.

Your Task

Use what you know about simple harmonic motion, causal relationships, the relationship between structure and function in nature, and the importance of patterns to design and carry out a series of experiments to determine which variables do and which variables do not change the period of the pendulum.

The guiding question of this investigation is, ***What variables affect the period of a pendulum?***

Materials

You may use any of the following materials during your investigation:

Consumables
- Tape
- String

Equipment
- Safety glasses or goggles (required)
- Electronic or triple beam balance
- Washers
- Paper clips
- Protractor
- Ruler
- Meterstick
- Stopwatch
- Scissors

To use a photogate system, you will need to have a sensor interface and a computer, tablet, or graphing calculator with data collection and analysis software. To use video analysis, you will need to have a video camera and a computer or tablet with video analysis software.

Safety Precautions

Follow all normal lab safety rules. In addition, take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Use caution when working with scissors. They are sharp and can cut or puncture skin.

4. Wash hands with soap and water after completing the lab.

Investigation Proposal Required? ☐ Yes ☐ No

Getting Started

To answer the guiding question, you will need to design and carry out several different experiments. Each experiment should look at one potential variable that may or may not affect the period of a pendulum. Some potential variables include the mass of the bob, the length of the pendulum, and the release angle. For each of your experiments, you must determine what type of data you need to collect, how you will collect it, and how you will analyze it before you begin.

To determine *what type of data you need to collect,* think about the following questions:

- What are the boundaries and components of the system you are studying?
- How can you describe the components of the system quantitatively?
- How could you keep track of changes in this system quantitatively?
- How might changes to the structure of pendulum change how it functions?
- What might be the underlying cause of a change in the period of a pendulum?
- What will be the independent variable and the dependent variable for each experiment?

To determine *how you will collect the data,* think about the following questions:

- How will you set up your pendulum?
- How will you measure the period of the pendulum?
- What will you need to hold constant during each experiment?
- What conditions need to be satisfied to establish a cause-and-effect relationship?
- What measurement scale or scales should you use to collect data?
- How will you make sure that your data are of high quality (i.e., how will you reduce error)?
- How will you keep track of and organize the data you collect?

To determine *how you will analyze the data,* think about the following questions:

- What type of calculations will you need to make?
- What types of patterns might you look for as you analyze your data?
- How could you use mathematics to show a cause-and-effect relationship?
- What type of table or graph could you create to help make sense of your data?

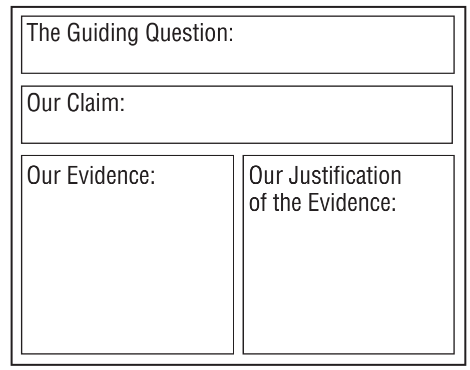
Connections to the Nature of Scientific Knowledge and Scientific Inquiry

As you work through your investigation, you may want to consider

- the difference between data and evidence in science, and
- the nature and role of experiments in science.

FIGURE L13.3

Argument presentation on a whiteboard



Initial Argument

Once your group has finished collecting and analyzing your data, your group will need to develop an initial argument. Your initial argument needs to include a claim, evidence to support your claim, and a justification of the evidence. The *claim* is your group's answer the guiding question. The *evidence* is an analysis and interpretation of your data. Finally, the *justification* of the evidence is why your group thinks the evidence matters. The justification of the evidence is important because scientists can use different kinds of evidence to support their claims. Your group will create your initial argument on a whiteboard. Your whiteboard should include all the information shown in Figure L13.3.

Argumentation Session

The argumentation session allows all of the groups to share their arguments. One or two members of each group will stay at the lab station to share that group's argument, while the other members of the group go to the other lab stations to listen to and critique the other arguments. This is similar to what scientists do when they propose, support, evaluate, and refine new ideas during a poster session at a conference. If you are presenting your group's argument, your goal is to share your ideas and answer questions. You should also keep a record of the critiques and suggestions made by your classmates so you can use this feedback to make your initial argument stronger. You can keep track of specific critiques and suggestions for improvement that your classmates mention in the space below.

Critiques about our initial argument and suggestions for improvement:

If you are critiquing your classmates' arguments, your goal is to look for mistakes in their arguments and offer suggestions for improvement so these mistakes can be fixed. You should look for ways to make your initial argument stronger by looking for things that the other groups did well. You can keep track of interesting ideas that you see and hear during the argumentation in the space below. You can also use this space to keep track of any questions that you will need to discuss with your team.

Interesting ideas from other groups or questions to take back to my group:

Once the argumentation session is complete, you will have a chance to meet with your group and revise your initial argument. Your group might need to gather more data or design a way to test one or more alternative claims as part of this process. Remember, your goal at this stage of the investigation is to develop the best argument possible.

Report

Once you have completed your research, you will need to prepare an *investigation report* that consists of three sections. Each section should provide an answer to the following questions:

1. What question were you trying to answer and why?
2. What did you do to answer your question and why?
3. What is your argument?

Your report should answer these questions in two pages or less. This report must be typed, and any diagrams, figures, or tables should be embedded into the document. Be sure to write in a persuasive style; you are trying to convince others that your claim is acceptable or valid!

Reference

Jeremy Norman's HistoryofInformation.com. 2016. Huygens invents the pendulum clock, increasing accuracy sixty fold (1656). *www.historyofinformation.com/expanded.php?id=3506.*

Checkout Questions

Lab 13. Simple Harmonic Motion and Pendulums: What Variables Affect the Period of a Pendulum?

1. The equation for the period of a pendulum is $T = 2\pi\sqrt{(L/\mathbf{g})}$, where T is the period, L is the length of the pendulum, and **g** is the acceleration due to gravity. If a person were to take a pendulum to the Moon, which has a gravitation pull approximately one-sixth that of Earth, what would happen to the period of the pendulum?

    a. The period would increase.
    b. The period would decrease.
    c. The period would stay the same.

    How do you know?

2. Why does the mass of bob have no effect on the period of a pendulum?

3. It is equally important for scientists to identify variables that do have a cause-and-effect relationship and those variables that do not have a cause-and-effect relationship.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about pendulums.

4. Scientists use the term *data* when they are talking about observations and the term *evidence* when they are talking about measurements.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about pendulums.

5. Why is important to look for patterns in science? In your answer, be sure to include one example from your investigation on pendulums and at least one more example from another investigation you have conducted in either this class or another science class.

6. Scientists often examine the structure of an object or material during an investigation. Explain why it is useful to examine the structure of an object or material, using an example from your investigation about pendulums.

7. Experiments are one of the most powerful approaches to answering questions in science. Identify the components of an experiment and explain why they are so important in science, using an example from your investigation about pendulums.

Teacher Notes

Lab 14. Simple Harmonic Motion and Springs: What Is the Mathematical Model of the Simple Harmonic Motion of a Mass Hanging From a Spring?

Purpose

The purpose of this lab is to *introduce* students to the core idea of forces and motion, part of the disciplinary core idea (DCI) of Motion and Stability: Forces and Interactions from the *NGSS,* by having them explore the simple harmonic motion of a mass hanging on a spring. This lab also gives students an opportunity to learn about the crosscutting concepts (CCs) of (a) Patterns, (b) Systems and System Models, and (c) Stability and Change from the *NGSS.* In addition, this lab can be used to help students understand two big ideas from AP Physics: (a) the interactions of an object with other objects can be described by forces and (b) interactions between systems can result in changes in those systems. As part of the explicit and reflective discussion, students will also learn about (a) how scientists use different methods to answer different types of questions and (b) the role of imagination and creativity in science.

Underlying Physics Concepts

The position of a mass, $\mathbf{s}(t)$, in terms of time, t, can be described in Equation 14.1, where A is the amplitude, B is the frequency, $\mathbf{C}$ is the initial displacement from equilibrium, and D is the phase shift. In SI units, position in terms of time and amplitude is measured in meters (m); frequency is measured either in hertz (Hz) or in radians per second (rad/s); initial displacement from equilibrium is measured in meters (m); and the phase shift is measured in seconds (s).

(Equation 14.1) $$\mathbf{s}(t) = \mathbf{C} + A\cos B\,(t - D)$$

Students will be able to develop a mathematical model of the simple harmonic motion of a mass hanging from a spring through two important steps: (1) collecting position-time data of a mass-spring system and (2) using graphical analysis software to graph the data they collected. The sinusoidal nature of the harmonic motion should suggest either a sine or cosine wave, and although it is commonplace to use cosine, a simple phase shift of the sine curve will yield the same result. In aiding students to find the parameters A, B, C, and D, consider asking them to compare the general cosine curve from Equation 14.1 with the data they collected. The following explanations and equations could be useful as students develop their mathematical model.

The amplitude, A, is equivalent to the distance from rest (equilibrium) to the maximum or minimum value, as shown in Equation 14.2.

$$\textbf{(Equation 14.2)} \quad A = \frac{\mathbf{s}(t)_{max} - \mathbf{s}(t)_{min}}{2}$$

The frequency, B, can be found by using Equation 14.3, which relates the observed period to the frequency, with observed period measured in seconds (s) and frequency measured in hertz (Hz) or radians per second (rad/s). To calculate the observed period, select two values of time, say t_1 and t_2, such that $\mathbf{s}(t_1) = \mathbf{s}(t_2)$, and calculate $t_2 - t_1$.

$$\textbf{(Equation 14.3)} \quad \textit{observed period} = \frac{2\pi}{B}$$

The distance from rest or equilibrium, **C,** referred to mathematically as vertical shift, is calculated by averaging the maximum and minimum values and is shown in Equation 14.4, with **C,** $\mathbf{s}(t)_{\max}$ and $\mathbf{s}(t)_{\min}$ all measured in meters (m).

$$\textbf{(Equation 14.4)} \quad \mathbf{C} = \frac{\mathbf{s}(t)_{max} + \mathbf{s}(t)_{min}}{2}$$

The phase shift, D, is the amount of time elapsed from $t = 0$ to the first maximum.

Timeline

The instructional time needed to complete this lab investigation is 200–280 minutes. Appendix 3 (p. 531) provides options for implementing this lab investigation over several class periods. Option E (280 minutes) should be used if students are unfamiliar with scientific writing, because this option provides extra instructional time for scaffolding the writing process. You can scaffold the writing process by modeling, providing examples, and providing hints as students write each section of the report. Option E can also be used if students are unfamiliar with any of the data collection and analysis tools. Option F (200 minutes) should be used if students are familiar with scientific writing and have developed the skills needed to write an investigation report on their own. In option F, students complete stage 6 (writing the investigation report) and stage 8 (revising the investigation report) as homework.

Materials and Preparation

The materials needed to implement this investigation are listed in Table 14.1. The equipment can be purchased from a science supply company such as Carolina, Flinn Scientific, PASCO Scientific, Vernier, or Ward's Science. Graphical analysis software can be purchased from Vernier (Logger *Pro*) or PASCO (SPARKvue or Capstone). These companies also have apps that can be used on Apple- or Android-based tablets. We recommend consulting with your school's information technology coordinator to determine the best option for your students.

TABLE 14.1

Materials list for Lab 14

Item	Quantity
Safety glasses or goggles	1 per student
Support stand	1 per group
Suspension hook clamp	1 per group
Hanging mass set	1 per group
Springs (variety)	Class set
Motion detector/sensor	1 per group
Interface for motion detector/sensor	1 per group
Computer, tablet, or graphing calculator with data collection and analysis software	1 per group
Investigation Proposal C (optional)	1 per group
Whiteboard, 2' × 3'*	1 per group
Lab Handout	1 per student
Peer-review guide and teacher scoring rubric	1 per student
Checkout Questions	1 per student

* As an alternative, students can use computer and presentation software such as Microsoft PowerPoint or Apple Keynote to create their arguments.

Be sure to use a set routine for distributing and collecting the materials during the lab investigation. One option is to set up the materials for each group at each group's lab station before class begins. This option works well when there is a dedicated section of the classroom for lab work and the materials are large and difficult to move (such as a dynamics track). A second option is to have all the materials on a table or cart at a central location. You can then assign a member of each group to be the "materials manager." This individual is responsible for collecting all the materials his or her group needs from the table or cart during class and for returning all the materials at the end of the class. This option works well when the materials are small and easy to move (such as stopwatches, metersticks, or hanging masses). It also makes it easy to inventory the materials at the end of the class before students leave for the day.

Safety Precautions

Remind students to follow all normal lab safety rules. In addition, tell students to take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Wash hands with soap and water after completing the lab.

Topics for the Explicit and Reflective Discussion

Reflecting on the Use of Core Ideas and Crosscutting Concepts During the Investigation

Teachers should begin the explicit and reflective discussion by asking students to discuss what they know about the core idea they used during the investigation. The following are some important concepts related to the core idea of forces and motion that students will need to develop a mathematical model of the simple harmonic motion of a mass hanging from a spring:

- A reference frame is needed to determine the direction and the magnitude of the displacement, velocity, and acceleration of an object.
- Force is considered a vector quantity because a force has both magnitude and direction.
- A restoring force can result in oscillatory motion.
- Simple harmonic motion occurs when a restoring force is directly proportional to the displacement of an object and acts in the direction opposite to that of displacement.

To help students reflect on what they know about forces and motion, we recommend showing them two or three images using presentation software that help illustrate these important ideas. You can then ask the students the following questions to encourage them to share how they are thinking about these important concepts:

1. What do we see going on in this image?
2. Does anyone have anything else to add?
3. What might be going on that we can’t see?

4. What are some things that we are not sure about here?

You can then encourage students to think about how CCs played a role in their investigation. There are at least three CCs that students need to use to develop a mathematical model of the simple harmonic motion of a mass hanging from a spring: (a) Patterns, (b) Systems and System Models, and (c) Stability and Change (see Appendix 2 [p. 527] for a brief description of these CCs). To help students reflect on what they know about these CCs, we recommend asking them the following questions:

1. Why is it important to look for patterns during an investigation?
2. What patterns did you identify during your investigation? What did the identification of these patterns allow you to do?
3. Why do scientists often need to define a system and then develop a model of it as part of an investigation?
4. How did you use a model during your investigation to understand the motion of a mass hanging from a spring?
5. Why is it important to think about what controls or affects the rate of change in system?
6. Which factors might have controlled the rate of change in the movement of the mass hanging from a spring? What did testing these factors systematically allow you to do?

You can then encourage the students to think about how they used all these different concepts to help answer the guiding question and why it is important to use these ideas to help justify their evidence for their final arguments. Be sure to remind your students to explain why they included the evidence in their arguments and make the assumptions underlying their analysis and interpretation of the data explicit in order to provide an adequate justification of their evidence.

Reflecting on Ways to Design Better Investigations

It is important for students to reflect on the strengths and weaknesses of the investigation they designed during the explicit and reflective discussion. Students should therefore be encouraged to discuss ways to eliminate potential flaws, measurement errors, or sources of uncertainty in their investigations. To help students be more reflective about the design of their investigation and what they can do to make their investigations more rigorous in the future, you can ask them the following questions:

1. What were some of the strengths of the way you planned and carried out your investigation? In other words, what made it scientific?

2. What were some of the weaknesses of the way you planned and carried out your investigation? In other words, what made it less scientific?
3. What rules can we make, as a class, to ensure that our next investigation is more scientific?

Reflecting on the Nature of Scientific Knowledge and Scientific Inquiry

This investigation can be used to illustrate two important concepts related to the nature of scientific knowledge and the nature of scientific inquiry: (a) how scientists use different methods to answer different types of questions and (b) the role of imagination and creativity in science (see Appendix 2 for a brief description of these two concepts). Be sure to review these concepts during and at the end of the explicit and reflective discussion. To help students think about these concepts in relation to what they did during the lab, you can ask them the following questions:

1. There is no universal step-by-step scientific method that all scientists follow. Why do you think there is no universal scientific method?
2. Think about what you did during this investigation. How would you describe the method you used to develop a mathematical model of the simple harmonic motion of a mass hanging from a spring? Why would you call it that?
3. Some people think that there is no room for imagination or creativity in science. What do you think?
4. Can you work with your group to come up with different ways that you needed to use your imagination or be creative during this investigation? Be ready to share in a few minutes.

You can also use presentation software or other techniques to encourage your students to think about these concepts. You can show one or more images of a "universal scientific method" that misrepresent the nature of scientific inquiry (see, e.g., *https://commons.wikimedia.org/wiki/File:The_Scientific_Method_as_an_Ongoing_Process.svg)* and ask students why each image is *not* a good representation of what scientists do to develop scientific knowledge. You can ask students to suggest revisions to the image that would make it more consistent with the way scientists develop scientific knowledge. You can also show students an image of the following quote by E. O. Wilson from *Letters to a Young Scientist* (2013) and ask them what they think he meant by it:

> The ideal scientist thinks like a poet and only later works like a bookkeeper. Keep in mind that innovators in both literature and science are basically dreamers and storytellers. In the early stages of the creation of both literature and science, everything in the mind is a story. There is an imagined ending, and usually an imagined beginning, and a selection of bits and pieces that might fit in between.

> In works of literature and science alike, any part can be changed, causing a ripple among the other parts, some of which are discarded and new ones added. (p. 74)

Be sure to remind your students that, to be proficient in science, it is important that they understand what counts as scientific knowledge and how that knowledge develops over time.

Hints for Implementing the Lab

- Allowing students to design their own procedures for collecting data gives students an opportunity to try, to fail, and to learn from their mistakes. However, you can scaffold students as they develop their procedure by having them fill out an investigation proposal. These proposals provide a way for you to offer students hints and suggestions without telling them how to do it. You can also check the proposals quickly during a class period. We recommend having the students fill out a different investigation proposal for each experiment. For this lab we suggest using Investigation Proposal C.
- Learn how to use the motion detector/sensor and the data collection and analysis software that the students will use before the lab begins. It is important for you to know how to use the equipment so you can help students when technical issues arise.
- Allow the students to become familiar with the motion detector/sensor and other equipment as part of the tool talk before they begin to design their investigation. Giving them 5–10 minutes to examine the equipment allows them to see what they can and cannot do with it. This also gives students a chance to begin thinking about what variables to test and how to control for other variables.
- We recommend an experimental setup where the spring oscillates vertically, as opposed to horizontally. This will provide students with more robust data. Furthermore, the dampening effects will be minimal.
- When students are modeling the spring, they will want to allow the spring to come to rest at the equilibrium position before they begin collecting data. They can then pull the spring to a displacement from equilibrium position and measure the displacement before releasing the spring. The initial displacement will be equal to the amplitude.
- Be sure to allow students to go back and re-collect data at the end of the argumentation session. Students often realize that they made numerous mistakes when they were collecting data as a result of their discussions during the argumentation session. The students, as a result, will want a chance to re-collect data, and the re-collection of data should be encouraged when time allows. This also offers an opportunity to discuss what scientists do when they realize a mistake is made inside the lab.

Connections to Standards

Table 14.2 highlights how the investigation can be used to address learning objectives from AP Physics 1; learning objectives from AP Physics C: Mechanics, *Common Core State Standards,* in English language arts (*CCSS ELA*); and *Common Core State Standards,* Mathematics (*CCSS Mathematics*).

TABLE 14.2

Lab 14 alignment with standards

***NGSS* performance expectations**	• None
AP Physics 1 learning objectives	• 3.A.1.1: The student is able to express the motion of an object using narrative, mathematical, and graphical representations. • 3.A.1.2: The student is able to design an experimental investigation of the motion of an object. • 3.A.1.3: The student is able to analyze experimental data describing the motion of an object and is able to express the results of the analysis using narrative, mathematical, and graphical representations. • 3.B.3.1: The student is able to predict which properties determine the motion of a simple harmonic oscillator and what the dependence of the motion is on those properties. • 3.B.3.2: The student is able to design a plan and collect data in order to ascertain the characteristics of the motion of a system undergoing oscillatory motion caused by a restoring force.
AP Physics C: Mechanics learning objectives	• I.A.1.b(1): Write down expressions for velocity and position as functions of time, and identify or sketch graphs of these quantities. • IA.2.c(1): Write down expressions for the horizontal and vertical components of velocity and position as functions of time, and sketch or identify graphs of these components. • I.F.1.a: Sketch or identify a graph of displacement as a function of time, and determine from such a graph the amplitude, period, and frequency of the motion. • I.F.1.b: Write down an appropriate expression for displacement of the form $A \sin \omega t$ or $A \cos \omega t$ to describe the motion. • I.F.2.c: Analyze problems in which a mass hangs from a spring and oscillates vertically.

continued

Table 14.2 (*continued*)

Literacy connections (*CCSS ELA*)	• *Reading:* Key ideas and details, craft and structure, integration of knowledge and ideas • *Writing:* Text types and purposes, production and distribution of writing, research to build and present knowledge, range of writing • *Speaking and listening:* Comprehension and collaboration, presentation of knowledge and ideas
Mathematics connections (*CCSS Mathematics*)	• *Mathematical practices:* Make sense of problems and persevere in solving them, reason abstractly and quantitatively, construct viable arguments and critique the reasoning of others, model with mathematics, use appropriate tools strategically, attend to precision, look for and make use of structure, look for and express regularity in repeated reasoning • *Number and quantity:* Reason quantitatively and use units to solve problems, represent and model with vector quantities, perform operations on vectors • *Algebra:* Interpret the structure of expressions, create equations that describe numbers or relationships, understand solving equations as a process of reasoning and explain the reasoning, solve equations and inequalities in one variable, represent and solve equations and inequalities graphically. • *Functions:* Understand the concept of a function and use function notation, interpret functions that arise in applications in terms of the context, analyze functions using different representations, build a function that models a relationship between two quantities, construct and compare linear and exponential models and solve problems, interpret expressions for functions in terms of the situation they model, extend the domain of trigonometric functions using the unit circle, model periodic phenomena with trigonometric functions, prove and apply trigonometric identities. • *Statistics and probability:* Summarize, represent, and interpret data on two categorical and quantitative variables; understand and evaluate random processes underlying statistical experiments; make inferences and justify conclusions from sample surveys, experiments, and observational studies

Reference

Wilson, E. O. 2013. *Letters to a young scientist.* New York: Liveright Publishing.

Lab Handout

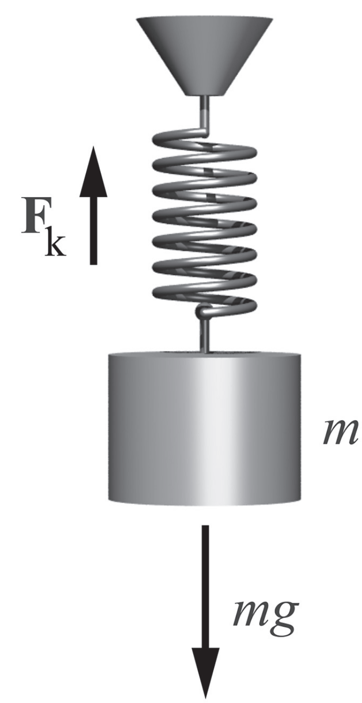
Lab 14. Simple Harmonic Motion and Springs: What Is the Mathematical Model of the Simple Harmonic Motion of a Mass Hanging From a Spring?

Introduction

A basic but important kind of motion is called simple harmonic motion. Simple harmonic motion is a type of periodic or oscillatory motion. An example of simple harmonic motion is the way a mass moves up and down when it is attached to a spring (see Figure L14.1). When the mass attached to a spring is not moving, the mass is said to be at equilibrium. When the mass is moved from the equilibrium position (such as when a person pulls down on the spring), a force from the spring ($\mathbf{F}_k$) acts on the mass to restore it to the equilibrium position. This force is called the restoring force. The further the mass is moved from the equilibrium position, the greater the restoring force becomes. In fact, the magnitude of the restoring force is directly proportional to the distance the mass is moved away from the equilibrium position (the displacement) and acts in the direction opposite to the direction of displacement.

We can explain the underlying cause of simple harmonic motion using Newton's second law of motion. Newton's second law of motion indicates that an object will accelerate when acted on by an unbalanced force. Thus, when an oscillator (in this case a mass attached to a spring) is disturbed from equilibrium, it accelerates in the general direction of the equilibrium position. When the mass reaches the equilibrium position, it has a non-zero velocity and the sum of the forces acting on it is zero. The mass will therefore move through the equilibrium position, at which point the restoring force increases until the mass reaches a maximum displacement from the equilibrium position. At the maximum displacement position, the restoring force is also at a maximum, while the velocity is equal to zero (0 m/s). This process repeats over time, which results in periodic or oscillatory motion.

FIGURE L14.1
A mass on a spring



In this investigation you will have an opportunity to examine the simple harmonic motion of a mass hanging on a spring. Your goal is to create a mathematical model that you can use to describe the vertical position of the mass in terms of time. Therefore, you will need to investigate the effect of different masses, release points, and types of springs during your investigation. It is important to note that your model will ignore dampening, the effect of slowing the mass-spring system down to a stop by frictional forces.

LAB 14

Your Task

Use what you know about simple harmonic motion, patterns, and stability and change in systems to develop a function that will allow you to model the motion of a mass hanging from a spring. To develop a mathematical model, you will need to design and carry out several experiments to determine how (a) different masses, (b) different release points, and (c) different spring types affect the motion of a mass hanging from a spring. Once you have developed your model, you will need to test it to determine if allows you to make accurate predictions about the vertical position of the mass in terms of time.

The guiding question of this investigation is, ***What is the mathematical model of the simple harmonic motion of a mass hanging from a spring?***

Materials

You may use any of the following materials during your investigation:

- Safety glasses or goggles (required)
- Support stand
- Suspension hook clamp
- Hanging mass set
- Springs (variety)
- Motion detector/sensor
- Interface for motion detector/sensor
- Computer, tablet, or graphing calculator with data collection and analysis software

Safety Precautions

Follow all normal lab safety rules. In addition, take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Wash hands with soap and water after completing the lab.

Investigation Proposal Required? ☐ Yes ☐ No

Getting Started

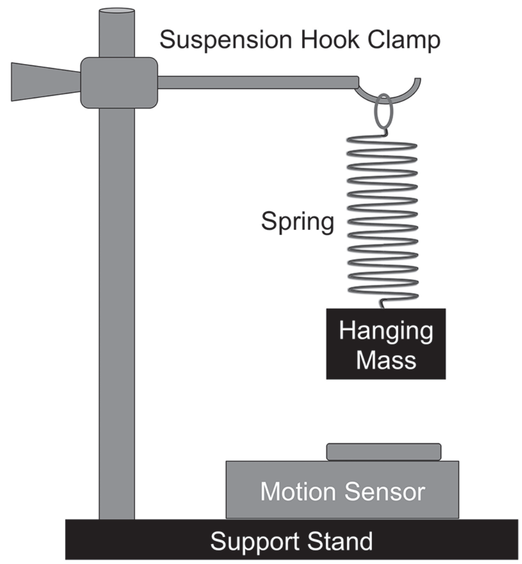
The first step in developing your mathematical model is to design and carry out three experiments. In the first experiment, you will need to determine how changing the mass affects the motion of a mass-spring system. You will then need to determine how changing the release point of the mass affects the motion of the mass-spring system. Finally, you will need to determine how changing the type of spring affects the motion of the mass-spring system. Figure L14.2 illustrates how you can use the available equipment to study the motion of a mass-spring system in each experiment. Before you can design your experiments, however, you must determine what type of data you need to collect, how you will collect it, and how you will analyze it.

To determine *what type of data you need to collect,* think about the following questions:

- What are the boundaries and components of the mass-spring system you are studying?
- Which factor(s) might control the rate of change in the mass-spring system?
- How could you keep track of changes in this system quantitatively?
- Under what conditions is the system stable, and under what conditions does it change?
- How will you measure the vertical position of the mass over time?
- What will be the independent variables and the dependent variables for each experiment?

FIGURE L14.2

One way to examine the motion of the mass-spring system using the available equipment



To determine *how you will collect the data,* think about the following questions:

- What other factors will you need to control during each experiment?
- What scale or scales should you use when you take your measurements?
- How will you make sure that your data are of high quality (i.e., how will you reduce error)?
- How will you keep track of and organize the data you collect?

To determine *how you will analyze the data,* think about the following questions:

- How much of your data is useful, given that you want to ignore dampening?
- What type of calculations will you need to make?
- What types of patterns might you look for as you analyze your data?
- What type of table or graph could you create to help make sense of your data?
- What types of equations can you use to describe motion that is periodic or harmonic?

Once you have determined how different masses, release points, and spring types affect the motion of a mass-spring system, your group will need to develop a mathematical model. The model must allow you to make accurate predictions about the vertical position of the mass in terms of time.

The last step in this investigation will be to test your model. To accomplish this goal, you can add different hanging masses (amounts that you did not test) to the end of one of the springs or try different release points (ones that you did not test) to determine whether your mathematical model helps you make accurate predictions. If you are able to use your model to make accurate predictions, then you will be able to generate the evidence you need to convince others that it is a valid and acceptable model of the simple harmonic motion of a mass hanging from a spring.

Connections to the Nature of Scientific Knowledge and Scientific Inquiry

As you work through your investigation, you may want to consider

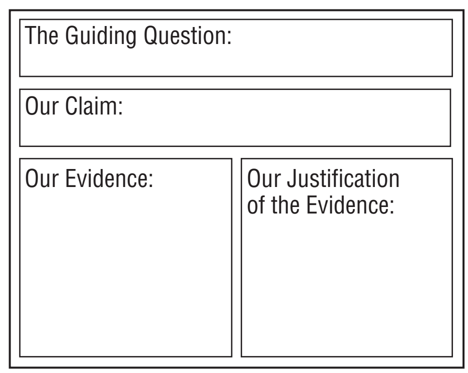
- how scientists use different methods to answer different types of questions, and
- the role of imagination and creativity in science.

Initial Argument

Once your group has finished collecting and analyzing your data, your group will need to develop an initial argument. Your argument must include a claim, evidence to support your claim, and a justification of the evidence. The *claim* is your group's answer to the guiding question. The *evidence* is an analysis and interpretation of your data. Finally, the *justification* of the evidence is why your group thinks the evidence matters. The justification of the evidence is important because scientists can use different kinds of evidence to support their claims. Your group will create your initial argument on a whiteboard. Your whiteboard should include all the information shown in Figure L14.3.

FIGURE L14.3

Argument presentation on a whiteboard



Argumentation Session

The argumentation session allows all of the groups to share their arguments. One or two members of each group will stay at the lab station to share that group's argument, while the other members of the group go to the other lab stations to listen to and critique the other arguments. This is similar to what scientists do when they propose, support, evaluate, and refine new ideas during a poster session at a conference. If you are presenting your group's argument, your goal is to share your ideas and answer questions. You should also keep a record of the critiques and suggestions made by your classmates so you can use this feedback to make your initial argument stronger. You can keep track of specific critiques and suggestions for improvement that your classmates mention in the space below.

Critiques about our initial argument and suggestions for improvement:

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Interesting ideas from other groups or questions to take back to my group:

Once the argumentation session is complete, you will have a chance to meet with your group and revise your initial argument. Your group might need to gather more data or design a way to test one or more alternative claims as part of this process. Remember, your goal at this stage of the investigation is to develop the best argument possible.

Report

Once you have completed your research, you will need to prepare an *investigation report* that consists of three sections. Each section should provide an answer to the following questions:

1. What question were you trying to answer and why?
2. What did you do to answer your question and why?
3. What is your argument?

Your report should answer these questions in two pages or less. This report must be typed, and any diagrams, figures, or tables should be embedded into the document. Be sure to write in a persuasive style; you are trying to convince others that your claim is acceptable or valid!

Checkout Questions

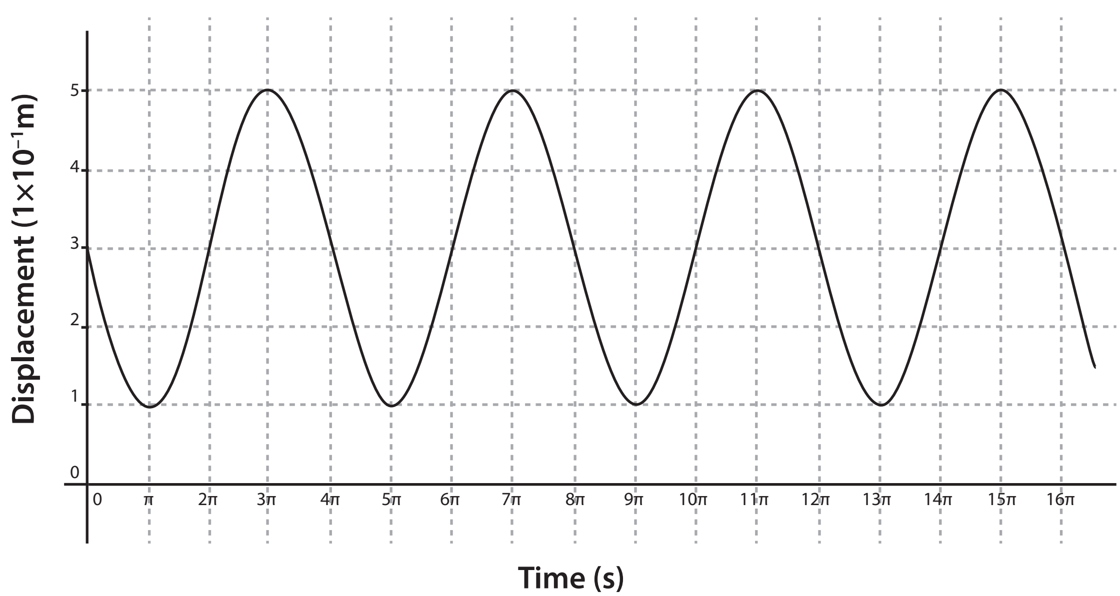
Lab 14. Simple Harmonic Motion and Springs: What Is the Mathematical Model of the Simple Harmonic Motion of a Mass Hanging From a Spring?

In most physics textbooks, the position of an object in simple harmonic motion is described using the equation below:

$$\mathbf{x} = A\cos(\omega t + \delta)$$

1. Given your model in terms of *A*, *B*, *C*, and *D*, define the parameters *A*, ω, and δ and discuss the meaning of each in terms of the position of the mass on a spring.

Use the graph below to answer questions 2 and 3.



2. What are the parameters A, B, C, and D for the general model $\mathbf{s}(t) = \mathbf{C} + A\cos B\,(t - D)$?

3. What are the parameters for A, ω, and δ for the model $x = A\cos(\omega t + \delta)$?

4. Scientists do not need to be creative or have a good imagination.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about simple harmonic motion and springs.

5. It is important to understand what makes a system stable or unstable and what contributes to the rates of change in a system.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about simple harmonic motion and springs.

6. Scientists use different methods to answer different types of questions. Explain how the type of question a scientist asks affects the methods he or she uses to answer those questions, using an example from your investigation about simple harmonic motion and springs.

7. Scientists often look for and try to explain patterns in nature. Explain why it is useful to look for and explain patterns in nature, using an example from your investigation about simple harmonic motion and springs.

8. Models in science can be physical, conceptual, or mathematical. Explain the difference in these types of models and discuss the strengths and weaknesses of each type of model, using an example from your investigation about simple harmonic motion and springs.

Application Lab

Teacher Notes

Lab 15. Simple Harmonic Motion and Rubber Bands: Under What Conditions Do Rubber Bands Obey Hooke's Law?

Purpose

The purpose of this lab is for students to *apply* what they know about the core idea of forces and motion, part of the disciplinary core idea (DCI) of Motion and Stability: Forces and Interactions from the *NGSS,* to determine if a mass hanging from a rubber band obeys Hooke's law. This lab also gives students an opportunity to learn about the crosscutting concepts (CCs) of (a) Systems and System Models and (b) Stability and Change from the *NGSS.* In addition, this lab can be used to help students understand two big ideas from AP Physics: (a) fields existing in space can be used to explain interactions and (b) the interactions of an object with other objects can be described by forces. As part of the explicit and reflective discussion, students will also learn about (a) how the culture of science, societal needs, and current events influence the work of scientists; and (b) the role of imagination and creativity in science.

Underlying Physics Concepts

For harmonic oscillators that undergo compression and expansion (such as a spring), Hooke's law is a reliable description of the relationship between the restoring force and the displacement from equilibrium of the oscillator. Conceptually, Hooke's law states that the restoring force is directly proportional to the displacement from equilibrium. Mathematically, Hooke's law is described by Equation 15.1, where **F** is the restoring force, **x** is the displacement from equilibrium, and k is the spring constant. In SI units, force is measured in newtons (N), displacement is measured in meters (m), and the spring constant has units of newtons per meter (N/m).

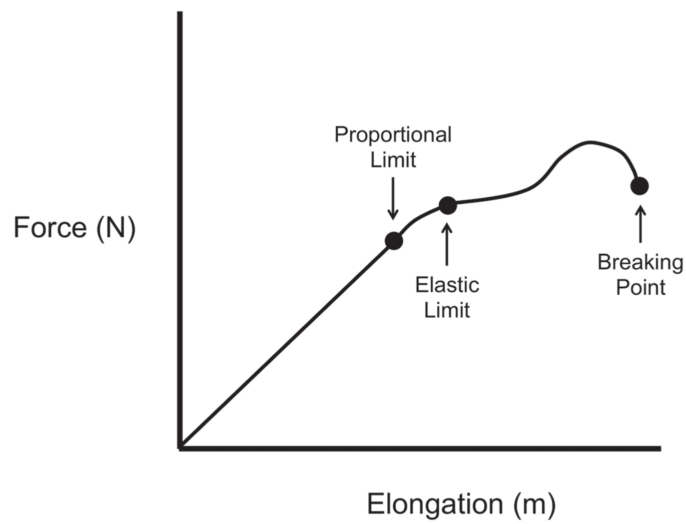
$$\textbf{(Equation 15.1)} \quad \mathbf{F} = -k\mathbf{x}$$

Yet, Hooke's Law only applies to a small range of compressions or extensions. Above this range of compression or extension, the oscillator becomes deformed and will no longer return to its natural equilibrium position. That is, if too much force is used to compress or extend the oscillator, the oscillator will become deformed. In the case of a bungee cord or a rubber band, this means that it will be permanently "stretched out."

Figure 15.1 shows a graph of the applied force to stretch an oscillator (spring, bungee, or rubber band) versus the elongation (i.e., the distance an oscillator is stretched). There are several points that are important to identify on the graph in Figure 15.1. The first point is the *proportional limit,* which is the largest amount of force that can be applied to stretch the oscillator such that the oscillator will return to its normal shape upon release of the force. For any force less than or equal to the proportional limit, the oscillator will obey Hooke's law. For this lab, this means that when a mass is placed at the end of the rubber band, if $m\mathbf{g}$ is less than or equal to the proportional limit, then the rubber band will obey Hooke's law and oscillate around an equilibrium point.

FIGURE 15.1

Stress curve for a mass on a rubber band



The second point on the graph is the *elastic limit*. The elastic limit and the proportional limit define a range of forces that have unique properties with respect to the oscillator. In this range of forces, the linear relationship between the force applied to stretch the oscillator (e.g., the spring or rubber band) and the elongation no longer holds. Instead, a very complex relationship between the force applied and the elongation exists, and the mathematics required to model this relationship is beyond the scope of a high school physics course. Although no linear relationship exists in this range of forces, as long as the force used to stretch the oscillator is less than or equal to the elastic limit, the oscillator will return to its normal shape upon release of the applied force. For this lab, it means the rubber band will return to its original shape and size.

When a force greater than the elastic limit is applied to the oscillator, this force results in the permanent deformation of the oscillator. With respect to this lab, when a large enough mass is placed on the end of a rubber band, the rubber band will become "permanently stretched out." There is, however, an upper limit on the amount of force that can be applied to stretch the oscillator. At this limit, the force is strong enough to break the oscillator, represented as the *breaking point* on the stress curve in Figure 15.1. With respect to a rubber band, if you put too much mass on the end, it will tear the rubber band.

There is one caveat to Hooke's law for a rubber band or a bungee cord oscillating around an equilibrium point. When a mass is placed on the rubber band, a new equilibrium position is created where the restoring force upward due to the stretch of the rubber band is equal to the gravitational force on the mass. Mathematically, this can be expressed as the elongation ($\mathbf{x}$) where $\Sigma\mathbf{F} = 0$, such that $m\mathbf{g} + k\mathbf{x} = 0$. Any additional force applied to stretch the rubber band will cause the mass to begin to oscillate.

Unlike springs, bungee cords and rubber bands do not have a restoring force when $\mathbf{x}$ is positive. If the mass is pulled slightly down, the restoring force will act to bring the mass back to the equilibrium point. The mass will return to the equilibrium point where the sum of the forces is zero. However, the velocity of the mass at the equilibrium point is in the positive direction, which results in the mass passing through the equilibrium point. Unlike springs, rubber bands are not easily compressed. When the mass moves through the equilibrium point to a positive displacement, there is no restoring force exerted on the mass by the rubber band. During this portion of the motion, the only force acting on the mass is the force due to gravity. Because this force is *not* proportional to the displacement from equilibrium, the rubber band does not obey Hooke's law during this portion of its motion.

Thus, when students are conducting their investigation, there are two potential answers to the question. Some groups may create investigations to determine the elastic limit, with the answer to the question being that the rubber band obeys Hooke's law up to a certain mass limit. Other groups may design their investigation such that they realize that a rubber band only obeys Hooke's law when the mass has negative displacement relative to the equilibrium point.

Timeline

The instructional time needed to complete this lab investigation is 200–280 minutes. Appendix 3 (p. 531) provides options for implementing this lab investigation over several class periods. Option E (280 minutes) should be used if students are unfamiliar with scientific writing, because this option provides extra instructional time for scaffolding the writing process. You can scaffold the writing process by modeling, providing examples, and providing hints as students write each section of the report. Option E can also be used if you are introducing students to the video analysis programs. Option F (200 minutes) should be used if students are familiar with scientific writing and have developed the skills needed to write an investigation report on their own. In option F, students complete stage 6 (writing the investigation report) and stage 8 (revising the investigation report) as homework.

Materials and Preparation

The materials needed for this investigation are listed in Table 15.1. The consumables and equipment can be purchased from a science supply company such as Carolina, Flinn Scientific, PASCO, Vernier, or Ward's Science. You can also purchase many of these materials from a general retail store such as Wal-Mart or Target. Video analysis software can be purchased from Vernier (Logger *Pro*) or PASCO (SPARKvue or Capstone). These companies also have apps that can be used on Apple- or Android-based tablets and cell phones. We recommend consulting with your school's information technology coordinator to determine the best option for your students.

TABLE 15.1

Materials list for lab 15

Item	Quantity
Consumables	
Rubber (nonlatex) bands	10 per group
Tape	As needed
Equipment and other materials	
Safety glasses or goggles	1 per student
Hanging mass set	1 per group
Paper clips	As needed
Ruler	1 per student
Support stand	1 per group
Electronic or triple beam balance	1 per group
Stopwatch	1 per student
Investigation Proposal A (optional)	1 per group
Whiteboard, 2' × 3'*	1 per group
Lab Handout	1 per student
Peer-review guide and teacher scoring rubric	1 per student
Checkout Questions	1 per student
Equipment for video analysis (optional)	
Video camera	1 per group
Computer or tablet with video analysis software	1 per group

* As an alternative, students can use computer and presentation software such as Microsoft PowerPoint or Apple Keynote to create their arguments.

Be sure to use a set routine for distributing and collecting the materials during the lab investigation. One option is to set up the materials for each group at each group's lab station before class begins. This option works well when there is a dedicated section of the classroom for lab work and the materials are large and difficult to move (such as a dynamics track). A second option is to have all the materials on a table or cart at a central location. You can then assign a member of each group to be the "materials manager." This individual is responsible for collecting all the materials his or her group needs from the table or cart during class and for returning all the materials at the end of the class. This option works well when the materials are small and easy to move (such as stopwatches, metersticks, or hanging masses). It also makes it easy to inventory the materials at the end of the class before students leave for the day.

Safety Precautions

Remind students to follow all normal lab safety rules. In addition, tell students to take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Wash hands with soap and water after completing the lab.

Topics for the Explicit and Reflective Discussion

Reflecting on the Use of Core Ideas and Crosscutting Concepts During the Investigation

Teachers should begin the explicit and reflective discussion by asking students to discuss what they know about the core idea they used during the investigation. The following are some important concepts related to the core idea of forces and motion that students will need to determine the conditions in which rubber bands obey Hooke's law:

- A reference frame is needed to determine the direction and the magnitude of the displacement, velocity, and acceleration of an object.
- Force is considered a vector quantity because a force has both magnitude and direction.
- A restoring force can result in oscillatory motion.
- Simple harmonic motion occurs when a restoring force is directly proportional to the displacement of an object and acts in the direction opposite to that of displacement.
- Hooke's law indicates that the strain (deformation) of an elastic object or material is proportional to the stress applied to it.

To help students reflect on what they know about forces and motion, we recommend showing them two or three images using presentation software that help illustrate these important ideas. You can then ask the students the following questions to encourage them to share how they are thinking about these important concepts:

1. What do we see going on in this image?
2. Does anyone have anything else to add?
3. What might be going on that we can't see?

4. What are some things that we are not sure about here?

You can then encourage students to think about how CCs played a role in their investigation. There are at least two CCs that students need to determine the conditions in which rubber bands obey Hooke's law: (a) Systems and System Models and (b) Stability and Change (see Appendix 2 [p. 527] for a brief description of these CCs). To help students reflect on what they know about these CCs, we recommend asking them the following questions:

1. Why do scientists often need to define a system and then develop a model of it as part of an investigation?
2. How did you use a model during your investigation to understand the motion of a mass hanging from a rubber band?
3. Why is it important to think about the conditions under which the behavior of a system is stable?
4. Under what conditions was the rubber band–mass system stable (i.e., under what conditions does the system obey Hooke's law)? Why is it important to understand the conditions under which a system is stable and when the system is not stable?

You can then encourage the students to think about how they used all these different concepts to help answer the guiding question and why it is important to use these ideas to help justify their evidence for their final arguments. Be sure to remind your students to explain why they included the evidence in their arguments and make the assumptions underlying their analysis and interpretation of the data explicit in order to provide an adequate justification of their evidence.

Reflecting on Ways to Design Better Investigations

It is important for students to reflect on the strengths and weaknesses of the investigation they designed during the explicit and reflective discussion. Students should therefore be encouraged to discuss ways to eliminate potential flaws, measurement errors, or sources of uncertainty in their investigations. To help students be more reflective about the design of their investigation and what they can do to make their investigations more rigorous in the future, you can ask them the following questions:

1. What were some of the strengths of the way you planned and carried out your investigation? In other words, what made it scientific?
2. What were some of the weaknesses of the way you planned and carried out your investigation? In other words, what made it less scientific?
3. What rules can we make, as a class, to ensure that our next investigation is more scientific?

Reflecting on the Nature of Scientific Knowledge and Scientific Inquiry

This investigation can be used to illustrate two important concepts related to the nature of scientific knowledge and the nature of scientific inquiry: (a) how the culture of science, societal needs, and current events influence the work of scientists; and (b) the role of imagination and creativity in science (see Appendix 2 for a brief description of these two concepts). Be sure to review these concepts during and at the end of the explicit and reflective discussion. To help students think about these concepts in relation to what they did during the lab, you can ask them the following questions:

1. People view some types of research as being more important than other types of research because of cultural values and current events. Can you come up with some examples of how cultural values and current events have influenced the work of scientists?
2. Scientists share a set of values, norms, and commitments that shape what counts as knowing, how to represent or communicate information, and how to interact with other scientists. Can you work with your group to come up with a rule that you can use to decide if something is science or not science? Be ready to share in a few minutes.
3. Some people think that there is no room for imagination or creativity in science. What do you think?
4. Can you work with your group to come up different ways that you needed to use your imagination or be creative during this investigation? Be ready to share in a few minutes.

You can also use presentation software or other techniques to encourage your students to think about these concepts. You can show examples of research projects that were influenced by cultural values and current events and ask students to think about was going on at the time and why that research was viewed as being important for the greater good. You can also show students an image of the following quote by E. O. Wilson from *Letters to a Young Scientist* (2013) and ask them what they think he meant by it:

> The ideal scientist thinks like a poet and only later works like a bookkeeper. Keep in mind that innovators in both literature and science are basically dreamers and storytellers. In the early stages of the creation of both literature and science, everything in the mind is a story. There is an imagined ending, and usually an imagined beginning, and a selection of bits and pieces that might fit in between. In works of literature and science alike, any part can be changed, causing a ripple among the other parts, some of which are discarded and new ones added. (p. 74)

Be sure to remind your students that, to be proficient in science, it is important that they understand what counts as scientific knowledge and how that knowledge develops over time.

Hints for Implementing the Lab

- Allowing students to design their own procedures for collecting data gives students an opportunity to try, to fail, and to learn from their mistakes. However, you can scaffold students as they develop their procedure by having them fill out an investigation proposal. These proposals provide a way for you to offer students hints and suggestions without telling them how to do it. You can also check the proposals quickly during a class period. For this lab we suggest using Investigation Proposal A.
- We suggest that you try this lab on your own before introducing it to the students. Different size and widths of rubber bands will have slightly different stress curves. Trying the lab yourself with different rubber bands will allow you to give students a set of masses that are appropriate for the rubber bands you are using.
- Allow the students to become familiar with the equipment and materials as part of the tool talk before they begin to design their investigation. Giving them 5–10 minutes to examine the equipment and materials will let them see what they can and cannot do with them. This also gives students a chance to begin thinking about what variables to test and how to control for other variables.
- For students who may need additional guidance, we suggest having them create force diagrams with respect to the oscillating mass. This will help students identify when the restoring force is obeying Hooke's law and when it is not.
- Be sure to allow students to go back and re-collect data at the end of the argumentation session. Students often realize that they made numerous mistakes when they were collecting data as a result of their discussions during the argumentation session. The students, as a result, will want a chance to re-collect data, and the re-collection of data should be encouraged when time allows. This also offers an opportunity to discuss what scientists do when they realize a mistake is made inside the lab.

If students use video analysis

- We suggest allowing students to familiarize themselves with the video analysis software before they finalize the procedure for the investigation, especially if they have not used such software previously. This gives students an opportunity to learn how to work with the software and to improve the quality of the video they take.

- Remind students to hold the video camera as still as possible. Any movement of the camera will introduce error into their analysis. If using actual camcorders, we recommend using a tripod to hold the camera steady. If students are using a camera on a cell phone or tablet, we recommend using a table to help steady the camera.
- Remind students to place a meterstick in the same field of view as the motion they are capturing with the video camera. Also, the meterstick should be approximately the same distance from the camera as the motion. Most video analysis software requires the user to define a scale in the video (this allows the software to establish distances and, subsequently, other variables dependent on distance and displacement).

Connections to Standards

Table 15.2 highlights how the investigation can be used to address learning objectives from AP Physics 1; learning objectives from AP Physics C: Mechanics, *Common Core State Standards,* in English language arts (*CCSS ELA*); and *Common Core State Standards,* Mathematics (*CCSS Mathematics*).

TABLE 15.2

Lab 15 alignment with standards

***NGSS* performance expectations**	• None
AP Physics 1 learning objectives	• 3.A.1.2: The student is able to design an experimental investigation of the motion of an object. • 3.A.1.3: The student is able to analyze experimental data describing the motion of an object and is able to express the results of the analysis using narrative, mathematical, and graphical representations. • 3.B.1.2: The student is able to design a plan to collect and analyze data for motion (static, constant, or accelerating) from force measurements and carry out an analysis to determine the relationship between the net force and the vector sum of the individual forces. • 3.B.3.c: Students should be able to calculate force and acceleration for any given displacement for an object oscillating on a spring. • 3.B.3.2: The student is able to design a plan and collect data in order to ascertain the characteristics of the motion of a system undergoing oscillatory motion caused by a restoring force. • 3.B.3.4: The student is able to construct a qualitative and/or a quantitative explanation of oscillatory behavior given evidence of a restoring force.

AP Physics C: Mechanics learning objectives	• I.C.2.b(4): Write an expression for the force exerted by an ideal spring and for the potential energy of a stretched or compressed spring. • I. F.2.b: Apply the expression for the period of oscillation of a mass on a spring. • I.F.2.c: Analyze problems in which a mass hangs from a spring and oscillates vertically.
Literacy connections (*CCSS ELA*)	• *Reading:* Key ideas and details, craft and structure, integration of knowledge and ideas • *Writing:* Text types and purposes, production and distribution of writing, research to build and present knowledge, range of writing • *Speaking and listening:* Comprehension and collaboration, presentation of knowledge and ideas
Mathematics connections (*CCSS Mathematics*)	• *Mathematical practices:* Make sense of problems and persevere in solving them, reason abstractly and quantitatively, construct viable arguments and critique the reasoning of others, model with mathematics, use appropriate tools strategically, attend to precision, look for and make use of structure, look for and express regularity in repeated reasoning • *Number and quantity:* Reason quantitatively and use units to solve problems, represent and model with vector quantities, perform operations on vectors • *Algebra:* Interpret the structure of expressions, write expressions in equivalent forms to solve problems, understand solving equations as a process of reasoning and explain the reasoning, solve equations and inequalities in one variable, represent and solve equations and inequalities graphically • *Functions:* Understand the concept of a function and use function notation, interpret functions that arise in applications in terms of the context, analyze functions using different representations, interpret expressions for functions in terms of the situation they model • *Statistics and probability:* Summarize, represent, and interpret data on two categorical and quantitative variables; interpret linear models; understand and evaluate random processes underlying statistical experiments; make inferences and justify conclusions from sample surveys, experiments, and observational studies

Reference

Wilson, E. O. 2013. *Letters to a young scientist.* New York: Liveright Publishing.

Lab Handout

Lab 15. Simple Harmonic Motion and Rubber Bands: Under What Conditions Do Rubber Bands Obey Hooke's Law?

Introduction

Harmonic oscillators are objects that move about an equilibrium point due to a restoring force. Two of the most common harmonic oscillators are pendulums and springs. Many objects that we encounter on a daily basis either contain a pendulum, such as a grandfather clock, or are a pendulum, such as the swings found on playgrounds. There are also many other objects that we use that incorporate springs. The shock absorbers found on cars, for example, are just large springs. Pendulums and springs, however, are not the only harmonic oscillators that are found in the world around us. For example, tire swings are a type of harmonic oscillator called a torsional oscillator because the restoring force from the rope causes the tire swing to twist back and forth (torsional motion is the motion of twisting). Another object that oscillates is a bungee jump ride (see Figure L15.1). When a person makes a bungee jump, he or she is attached to bungee cord and then dropped from a considerable height. That person then bounces up and down for the duration of the ride.

FIGURE L15.1

A bungee jump ride

Many oscillators obey the equations that describe simple harmonic motion. One of those equations is called Hooke's law, which states that the farther the oscillator is moved from its equilibrium point, the greater the restoring force on the oscillator. More specifically, the restoring force is directly proportional to the displacement the oscillator is from equilibrium. The equation for Hooke's law is $\mathbf{F} = -k\mathbf{x}$, where **F** is the restoring force, **x** is the displacement from equilibrium, and *k* is a constant of proportionality. This equation includes a negative sign because the restoring force always acts in the direction opposite the direction of displacement. For example, if the bungee cord is pulled in the down direction, then the restoring force acts in the up direction.

It is important to note, however, that Hooke's law is not valid for all ranges of possible displacements. For example, if a spring is pulled too far from its equilibrium point by a disturbing force, the spring will actually deform and remain stretched out, instead of returning to the equilibrium position. This caveat to Hooke's law is particularly important for those who incorporate an oscillator into the design of an amusement park ride. If the displacement exceeds the allowable range, the restoring force can no longer return the oscillator to equilibrium. For a bungee ride, this issue can pose safety risks, because the riders would continue to fall toward the ground. It is therefore very important to know how much mass can be added to a bungee cord before it deforms or breaks. One way to determine the range of mass that can safely be added to a bungee is to use a smaller-scale model of the system to explore the relationship between mass and displacement. In addition, we can use a rubber band to approximate the behavior of a bungee cord because rubber bands are much smaller and much less expensive. This type of modeling allows engineers to determine parameters they will need to consider when doing tests using actual bungee cords.

Your Task

Use what you know about forces, oscillation, systems and system models, and stability and change to design and carry out an investigation to determine the range of mass that can be added to a bungee cord so that it still obeys Hooke's law.

The guiding question of this investigation is, ***Under what conditions do rubber bands obey Hooke's law?***

Materials

You may use any of the following materials during your investigation:

Consumables
- Rubber bands
- Tape

Equipment
- Safety glasses or goggles (required)
- Hanging mass set
- Paper clips
- Ruler
- Support stand
- Electronic or triple beam balance
- Stopwatch

If you have access to the following equipment, you may also consider using a video camera and a computer or tablet with video analysis software.

Safety Precautions

Follow all normal lab safety rules. In addition, take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Wash hands with soap and water after completing the lab.

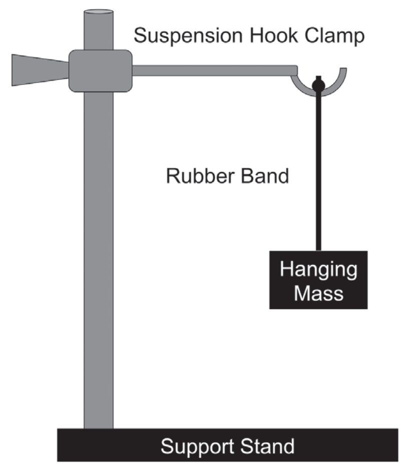
Investigation Proposal Required? ☐ Yes ☐ No

Getting Started

To answer the guiding question, you will need to design and carry out an investigation to determine the range of mass that can be added to a rubber band so that it still obeys Hooke's law. Figure L15.2 illustrates how you can use the available equipment to study the motion of a mass–rubber band system. Before you can design your investigation, however, you must determine what type of data you need to collect, how you will collect it, and how you will analyze it.

FIGURE L15.2

One way to examine the motion of the mass–rubber band system using the available equipment



To determine *what type of data you need to collect,* think about the following questions:

- What are the boundaries and components of the mass–rubber band system?
- How do the components of the system interact with each other?
- When is this system stable, and under which conditions does it change?
- How could you keep track of changes in this system quantitatively?
- How will you measure the motion of the hanging mass?
- What are the independent variables and the dependent variables for each experiment?

To determine *how you will collect the data,* think about the following questions:

- What other factors will you need to control during each experiment?
- What scale or scales should you use when you take your measurements?
- How will you make sure that your data are of high quality (i.e., how will you reduce error)?
- How will you keep track of and organize the data you collect?

To determine *how you will analyze the data,* think about the following questions:

- What types of patterns might you look for as you analyze your data?
- What type of table or graph could you create to help make sense of your data?
- How will you model the system to indicate under what parameters the harmonic motion is stable?

Connections to the Nature of Scientific Knowledge and Scientific Inquiry

As you work through your investigation, you may want to consider

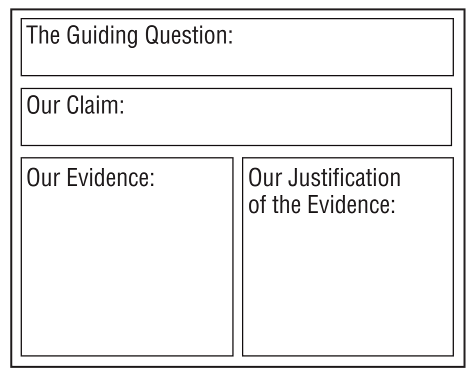
- how the culture of science, societal needs, and current events influence the work of scientists; and
- the role that imagination and creativity play in scientific research.

Initial Argument

Once your group has finished collecting and analyzing your data, your group will need to develop an initial argument. Your initial argument needs to include a claim, evidence to support your claim, and a justification of the evidence. The *claim* is your group's answer to the guiding question. The *evidence* is an analysis and interpretation of your data. Finally, the *justification* of the evidence is why your group thinks the evidence matters. The justification of the evidence is important because scientists can use different kinds of evidence to support their claims. Your group will create your initial argument on a whiteboard. Your whiteboard should include all the information shown in Figure L15.3.

FIGURE L15.3

Argument presentation on a whiteboard



Argumentation Session

The argumentation session allows all of the groups to share their arguments. One or two members of each group will stay at the lab station to share that group's argument, while the other members of the group go to the other lab stations to listen to and critique the other arguments. This is similar to what scientists do when they propose, support, evaluate, and refine new ideas during a poster session at a conference. If you are presenting your group's argument, your goal is to share your ideas and answer questions. You should also keep a record of the critiques and suggestions made by your classmates so you can use this feedback to make your initial argument stronger. You can keep track of specific critiques and suggestions for improvement that your classmates mention in the space below.

Critiques about our initial argument and suggestions for improvement:

If you are critiquing your classmates' arguments, your goal is to look for mistakes in their arguments and offer suggestions for improvement so these mistakes can be fixed. You should look for ways to make your initial argument stronger by looking for things that the other groups did well. You can keep track of interesting ideas that you see and hear during the argumentation in the space below. You can also use this space to keep track of any questions that you will need to discuss with your team.

Interesting ideas from other groups or questions to take back to my group:

Once the argumentation session is complete, you will have a chance to meet with your group and revise your initial argument. Your group might need to gather more data or design a way to test one or more alternative claims as part of this process. Remember, your goal at this stage of the investigation is to develop the best argument possible.

Report

Once you have completed your research, you will need to prepare an *investigation report* that consists of three sections. Each section should provide an answer to the following questions:

1. What question were you trying to answer and why?
2. What did you do to answer your question and why?
3. What is your argument?

Your report should answer these questions in two pages or less. This report must be typed, and any diagrams, figures, or tables should be embedded into the document. Be sure to write in a persuasive style; you are trying to convince others that your claim is acceptable or valid!

Checkout Questions

Lab 15. Simple Harmonic Motion and Rubber Bands: Under What Conditions Do Rubber Bands Obey Hooke's Law?

1. What is the mathematical relationship between the force acting on the rubber band and the elongation of the rubber band?

   Is the function linear as the force increases?

2. In springs, the spring constant *k* is a function of both the material the spring is made from and the shape of the spring. What factors do you think might affect the constant of proportionality relating the force on a rubber band to the elongation of the rubber band?

Explain your answer, based on what you observed during your investigation about Hooke's law and rubber bands.

3. The imagination and creativity of a scientist play an important role in planning and carrying out investigations.

    a. I agree with this statement.
    b. I disagree with this statement.

    Explain your answer, using an example from your investigation about Hooke's law and rubber bands.

4. The research done by a scientist is often influenced by what is important in society.

    a. I agree with this statement.
    b. I disagree with this statement.

Explain your answer, using an example from your investigation about Hooke's law and rubber bands.

5. Models are used to understand complex phenomena across the different scientific disciplines. Explain why models are so important, using an example from your investigation about Hooke's law and rubber bands.

6. Scientists often seek to identify the parameters under which a system is stable and what happens to the system when those parameters are exceeded. Explain why this is such an important research aim, using an example from your investigation about Hooke's law and rubber bands.

SECTION 6
Forces and Motion

Systems of Particles and Linear Momentum

Introduction Labs

Teacher Notes

Lab 16. Linear Momentum and Collisions: When Two Objects Collide and Stick Together, How Do the Initial Velocity and Mass of One of the Moving Objects Affect the Velocity of the Two Objects After the Collision?

Purpose

The purpose of this lab is to *introduce* students to the core idea of forces and motion, part of the disciplinary core idea (DCI) of Motion and Stability: Forces and Interactions from the *NGSS,* by giving them the opportunity to explore the conservation of momentum during a collision. This lab also gives students an opportunity to learn about the crosscutting concepts (CCs) of (a) Scale, Proportion, and Quantity; and (b) Energy and Matter: Flows, Cycles, and Conservation from the *NGSS.* In addition, this lab can be used to help students understand three big ideas from AP Physics: (a) the interactions of an object with other objects can be described by forces, (b) interactions between systems can result in changes in those systems, and (c) changes that occur as result of interactions are constrained by conservation laws. As part of the explicit and reflective discussion, students will also learn about (a) the difference between observations and inferences in science and (b) how the culture of science, societal needs, and current events influence the work of scientists.

Underlying Physics Concepts

Linear momentum is defined as the product of an object's mass (m) and velocity ($\mathbf{v}$). The mathematical relationship is shown in Equation 16.1. Because we already use m to represent mass in equations, physicists have agreed to use $\mathbf{p}$ to symbolize linear momentum. In SI units, momentum is measured in kilogram-meters per second (kg·m/s), mass is measured in kilograms (kg), and velocity is measured in meters per second (m/s).

$$\textbf{(Equation 16.1)} \quad \mathbf{p} = m\mathbf{v}$$

Among other quantities, linear momentum obeys a conservation law. The law of conservation of momentum is that the total momentum of a system of isolated objects remains constant. An *isolated system of objects* is a system of objects in which no outside forces act on the system as a whole or on the individual objects within the system. When analyzing the motion of objects to understand their momentum, we often define the system in such a way as to ignore the force of gravity on the objects, thereby treating the system as an isolated system. For example, when two pool balls collide on a pool table, we define the system such that we ignore the gravitational and normal forces acting on the balls and only include the force of the two balls on each other when they collide.

Although the law of conservation of momentum states that the total momentum of the system must be conserved, the momentum of each object can change within the system, such as when two objects collide. Mathematically, this is represented in Equation 16.2 (This equation is for linear motion; there are rotational analogues, but they can be ignored in this investigation). The subscripts 1 and 2 are used to denote each object, so $\mathbf{p_1}$ is the momentum of the first object and $\mathbf{p_2}$ is the momentum of the second object. The left side of the equation is the momentum of each object before the collision, and the right side of the equation is the momentum of each object after the collision. The symbol (′) on the right side of the equation is used to denote that those values represent the momentum after the collision, and it is pronounced "prime" (e.g., p_1' is read as "p one prime").

$$\textbf{(Equation 16.2)} \quad \mathbf{p_1} + \mathbf{p_2} = \mathbf{p_1}' + \mathbf{p_2}'$$

Using Equation 16.1, we can replace the value of momentum in Equation 16.2 with the product of each object's mass and velocity both before and after the collision, such that we get Equation 16.3:

$$\textbf{(Equation 16.3)} \quad m_1\mathbf{v_1} + m_2\mathbf{v_2} = m_1\mathbf{v_1}' + m_2\mathbf{v_2}'$$

Notice that on the right side of Equation 16.3 the prime symbol is only on the velocity for each object, respectively. That is, after the collision, we may say "v one prime." We do not, however, place a prime symbol on the mass, because we generally assume that the mass of each object does not change during the collision. Finally, Equation 16.3 is not restricted to two objects. If, for example, there was a collision between three objects, we could add the third object's momentum to both the right and left side of the equation.

In this lab, students explore a *perfectly inelastic collision,* or a collision where the objects stick together after they collide. Mathematically, this type of collision is represented in Equation 16.4.

$$\textbf{(Equation 16.4)} \quad m_1\mathbf{v_1} + m_2\mathbf{v_2} = (m_1 + m_2)\mathbf{v}'$$

Because the objects stick together, we can treat them as one object with a mass equal to the sum of the masses of the two individual objects. Finally, they will both move together after the collision with the same velocity. If we assume that the second object is stationary before the collision, then Equation 16.4 becomes Equation 16.5.

$$\textbf{(Equation 16.5)} \quad m_1\mathbf{v_1} = (m_1 + m_2)\mathbf{v}'$$

This means that before the collision only the first object has momentum. After the collision, when both objects stick together, they both have momentum and move together with the same velocity. We can rearrange this relationship to find the answer to the guiding question for the two relevant variables at the heart of this investigation.

The first task requires students to determine the effect of increased velocity for object 1 on the velocity of both objects after the collision. Using Equation 16.5, we find a linear relationship between the two velocities, given by the equation $\mathbf{v}' = (\frac{m_1}{m_1 + m_2})\mathbf{v_1}$. As the velocity of the first object increases, the velocity of both objects after the collision will increase linearly, with the slope of the line being equal to $(\frac{m_1}{m_1 + m_2})$.

The second task requires students to determine the effect of increasing the mass of the incoming object on the resultant velocity of the two objects after the collision. The equation governing this relationship remains $\mathbf{v}' = (\frac{m_1}{m_1 + m_2})\mathbf{v_1}$. However, in this case, $\mathbf{v_1}$ is constant. When increasing the mass of the incoming object, the resultant velocity of the two objects after the collision will also increase, but this relationship is not linear. If students were to graph this relationship, they would find that $\mathbf{v}'$ approaches $\mathbf{v_1}$ but that there is a horizontal asymptote at this point.

Timeline

The instructional time needed to complete this lab investigation is 220–280 minutes. Appendix 3 (p. 531) provides options for implementing this lab investigation over several class periods. Option A (280 minutes) should be used if students are unfamiliar with scientific writing, because this option provides extra instructional time for scaffolding the writing process. You can scaffold the writing process by modeling, providing examples, and providing hints as students write each section of the report. Option A can also be used if students are unfamiliar with any of the data collection and analysis tools. Option B (220 minutes) should be used if students are familiar with scientific writing and have developed the skills needed to write an investigation report on their own. In option F, students complete stage 6 (writing the investigation report) and stage 8 (revising the investigation report) as homework.

Materials and Preparation

The materials needed to implement this investigation are listed in Table 16.1. The items can be purchased from a science supply company such as Carolina, Flinn Scientific, PASCO, Vernier, or Ward's Science. The data collection and analysis software and/or the video analysis software) can be purchased from Vernier (Logger *Pro*) or PASCO Scientific (SPARKvue or Capstone). These companies also have apps that can be used on Apple- or Android-based tablets and cell phones. We recommend consulting with your school's information technology coordinator to determine the best option for your students.

TABLE 16.1

Materials list for Lab 16

Item	Quantity
Safety glasses or goggles	1 per student
Dynamics cart (with Velcro or magnetic bumpers)	2 per group
Dynamics track	1 per group
Motion detector/sensor	2 per group
Interface for motion detector/sensor (if used)	1 per group
Video camera	1 per group
Computer or tablet with data collection and analysis software (for use with motion detector/sensor) or video analysis software (for use with the video camera)	1 per group
Electronic or triple beam balance	1 per group
Cart picket fence	1 per group
Mass set	1 per group
Stopwatch	2–3 per group
Meterstick or ruler	1 per group
Whiteboard, 2' × 3'*	1 per group
Lab Handout	1 per student
Investigation Proposal C (optional)	2 per group
Peer-review guide and teacher scoring rubric	1 per student
Checkout Questions	1 per student

* As an alternative, students can use computer and presentation software such as Microsoft PowerPoint or Apple Keynote to create their arguments.

Be sure to use a set routine for distributing and collecting the materials during the lab investigation. One option is to set up the materials for each group at each group's lab station before class begins. This option works well when there is a dedicated section of the classroom for lab work and the materials are large and difficult to move (such as a dynamics track). A second option is to have all the materials on a table or cart at a central location. You can then assign a member of each group to be the "materials manager." This individual is responsible for collecting all the materials his or her group needs from the table or cart during class and for returning all the materials at the end of the class. This option works well when the materials are small and easy to move (such as stopwatches, metersticks, or hanging masses). It also makes it easy to inventory the materials at the end of the class before students leave for the day.

Safety Precautions

Remind students to follow all normal lab safety rules. In addition, tell students to take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Wash hands with soap and water after completing the lab.

Topics for the Explicit and Reflective Discussion

Reflecting on the Use of Core Ideas and Crosscutting Concepts During the Investigation

Teachers should begin the explicit and reflective discussion by asking students to discuss what they know about the core idea they used during the investigation. The following are some important concepts related to the core idea of forces and motion that students will need to explain what happens when two objects collide and stick together:

- A reference frame is needed to determine the direction and the magnitude of the displacement, velocity, and acceleration of an object.
- Force is considered a vector quantity because a force has both magnitude and direction.
- A *system* is an object or a collection of objects. An object is treated as if it has no internal structure.
- The boundary between a system and its environment is a decision made by the person considering the situation in order to simplify or otherwise assist in analysis.
- Conserved quantities are constant in an isolated or a closed system. An open system is one that exchanges any conserved quantity with its surroundings.
- Linear momentum is conserved in all systems.

To help students reflect on what they know about forces and motion, we recommend showing them two or three images using presentation software that help illustrate these important ideas. You can then ask the students the following questions to encourage them to share how they are thinking about these important concepts:

1. What do we see going on in this image?
2. Does anyone have anything else to add?

3. What might be going on that we can't see?
4. What are some things that we are not sure about here?

You can then encourage students to think about how CCs played a role in their investigation. There are at least two CCs that students need to explain what happens when two objects collide and stick together: (a) Scale, Proportion, and Quantity; and (b) Energy and Matter: Flows, Cycles, and Conservation (see Appendix 2 [p. 527] for a brief description of these CCs). To help students reflect on what they know about these CCs, we recommend asking them the following questions:

1. Why is it important keep track of changes in a system quantitatively during an investigation?
2. What did you keep track of quantitatively during your investigation? What did that allow you to do?
3. Scientists often attempt to track how energy and matter move into, out of, and within systems as part of an investigation. Why is this useful?
4. How did you attempt to track how matter moves within the system you were studying? What did tracking the movement of matter allow you to do during your investigation?

You can then encourage the students to think about how they used all these different concepts to help answer the guiding question and why it is important to use these ideas to help justify their evidence for their final arguments. Be sure to remind your students to explain why they included the evidence in their arguments and make the assumptions underlying their analysis and interpretation of the data explicit in order to provide an adequate justification of their evidence.

Reflecting on Ways to Design Better Investigations

It is important for students to reflect on the strengths and weaknesses of the investigation they designed during the explicit and reflective discussion. Students should therefore be encouraged to discuss ways to eliminate potential flaws, measurement errors, or sources of uncertainty in their investigations. To help students be more reflective about the design of their investigation and what they can do to make their investigations more rigorous in the future, you can ask them the following questions:

1. What were some of the strengths of the way you planned and carried out your investigation? In other words, what made it scientific?
2. What were some of the weaknesses of the way you planned and carried out your investigation? In other words, what made it less scientific?

3. What rules can we make, as a class, to ensure that our next investigation is more scientific?

Reflecting on the Nature of Scientific Knowledge and Scientific Inquiry

This investigation can be used to illustrate two important concepts related to the nature of scientific knowledge and the nature of scientific inquiry: (a) the difference between observations and inferences in science and (b) how the culture of science, societal needs, and current events influence the work of scientists (see Appendix 2 for a brief description of these two concepts). Be sure to review these concepts during and at the end of the explicit and reflective discussion. To help students think about these concepts in relation to what they did during the lab, you can ask them the following questions:

1. You had to make observations and inferences during your investigation. Can you give me some examples of these observations and inferences?
2. Can you work with your group to come up with a rule that you can use to decide if a piece of information is an observation or an inference? Be ready to share in a few minutes.
3. People view some types of research as being more important than other types of research because of cultural values and current events. Can you come up with some examples of how cultural values and current events have influenced the work of scientists?
4. Scientists share a set of values, norms, and commitments that shape what counts as knowing, how to represent or communicate information, and how to interact with other scientists. Can you work with your group to come up with a rule that you can use to decide if something is science or not science? Be ready to share in a few minutes.

You can also use presentation software or other techniques to encourage your students to think about these concepts. You can show examples of information from the investigation that are either observations or inferences and ask students to classify each example and explain their thinking. You can also show examples of research projects that were influenced by cultural values and current events and ask students to think about what was going on at the time and why that research was viewed as being important for the greater good.

Be sure to remind your students that, to be proficient in science, it is important that they understand what counts as scientific knowledge and how that knowledge develops over time.

Hints for Implementing the Lab

- In this lab, students will have to conduct two different experiments to determine (1) how changing the velocity of a moving object affects the velocity of that object and a second object after a collision, when holding mass constant; and (2) how changing the mass of the moving object affects the velocity of both objects after the collision, when holding the incoming velocity of the moving object constant.
- Allowing students to design their own procedures for collecting data gives students an opportunity to try, to fail, and to learn from their mistakes. However, you can scaffold students as they develop their procedure by having them fill out an investigation proposal. These proposals provide a way for you to offer students hints and suggestions without telling them how to do it. You can also check the proposals quickly during a class period. We recommend having students fill out a proposal for each experiment. For this lab we suggest using Investigation Proposal C.
- To determine the velocity of the carts, we recommend using a motion detector/sensor attached to the track as shown in Figure L16.3 in the Lab Handout (p. 357); as an alternative, students can conduct a video analysis of the motion of the carts.
- If students use motion detectors/sensors, they can use either one or two motion detectors (see Figure L16.3 in the Lab Handout). If they use only one motion detector, they will want to make sure that it is on the side of the track with the cart that has a non-zero initial velocity (see the next hint). If students use two motion detectors (one for each cart), after the collision, they will record equal but opposite values for the velocity of the system. This is because the velocity after the collision will be away from the first motion detector (i.e., a positive direction) and toward the second motion detector (i.e., a negative direction). This provides an opportunity to reinforce the importance of defining positive and negative reference frames.
- Although it is not necessary, we recommend having the second object remain stationary during the collision. This way, the value of $m_2\mathbf{v_2}$ in equation 16.4 is zero. In other words, the easiest way to control for the momentum of the second object is for the momentum of the second object to be equal to zero. Because the second object has a mass greater than zero, the velocity of the second object must be zero if the momentum of the object is zero.
- When adding masses to the cart to investigate the relationship between the increased mass and the resulting velocity, it is important to add sufficient mass relative to the mass of the cart. For example, if the mass of each cart is 100 g, adding an additional 1 g mass will not have much of an effect on the outcome.
- Learn how to use the dynamics track before the lab begins. It is important for you to know how to use the equipment so you can help students when technical issues

arise. Some collision tracks require pressurized air; others use magnetic fields, which require access to power outlets, and others just have carts on wheels that have a very small coefficient of friction.

- Allow the students to become familiar with the dynamics track as part of the tool talk before they begin to design their investigation. Giving them 5–10 minutes to examine the equipment will let them see what they can and cannot do with it. This also gives students a chance to begin thinking about what variables to test and how to control for other variables.
- Be sure to allow students to go back and re-collect data at the end of the argumentation session. Students often realize that they made numerous mistakes when they were collecting data as a result of their discussions during the argumentation session. The students, as a result, will want a chance to re-collect data, and the re-collection of data should be encouraged when time allows. This also offers an opportunity to discuss what scientists do when they realize a mistake is made inside the lab.

If students use a motion detector/sensor

- Learn how to use the motion detector/sensor and the data collection and analysis software before the lab begins. It is important for you to know how to use the equipment and software so you can help students when technical issues arise.
- Allow the students to become familiar with the motion detector/sensor and data collection and analysis software as part of the tool talk before they begin to design their investigation. Giving them 5–10 minutes to examine the equipment and software will let them see what they can and cannot do with it.

If students use video analysis

- We suggest allowing students to familiarize themselves with the video analysis software before they finalize the procedure for the investigation, especially if they have not used such software previously. This gives students an opportunity to learn how to work with the software and to improve the quality of the video they take.
- Remind students to hold the video camera as still as possible. Any movement of the camera will introduce error into their analysis. If using actual camcorders, we recommend using a tripod to hold the camera steady. If students are using a camera on a cell phone or tablet, we recommend using a table to help steady the camera.
- Remind students to place a meterstick in the same field of view as the motion they are capturing with the video camera. Also, the meterstick should be approximately the same distance from the camera as the motion. Most video analysis software

requires the user to define a scale in the video (this allows the software to establish distances and, subsequently, other variables dependent on distance and displacement).

Connections to Standards

Table 16.2 highlights how the investigation can be used to address specific performance expectations from the *NGSS;* learning objectives from AP Physics 1; learning objectives from AP Physics C: Mechanics, *Common Core State Standards,* in English language arts (*CCSS ELA*); and *Common Core State Standards,* Mathematics (*CCSS Mathematics*).

TABLE 16.2

Lab 16 alignment with standards

***NGSS* performance expectation**	• HS-PS2-2: Use mathematical representations to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system.
AP Physics 1 learning objectives	• 3.A.1.1: The student is able to express the motion of an object using narrative, mathematical, and graphical representations. • 3.A.1.2: The student is able to design an experimental investigation of the motion of an object. • 3.A.1.3: The student is able to analyze experimental data describing the motion of an object and is able to express the results of the analysis using narrative, mathematical, and graphical representations. • 4.B.1.1: The student is able to calculate the change in linear momentum of a two-object system with constant mass in linear motion from a representation of the system (data, graphs, etc.). • 4.B.1.2: The student is able to analyze data to find the change in linear momentum for a constant-mass system using the product of the mass and the change in velocity of the center of mass. • 5.A.2.1: The student is able to define open and closed/isolated systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. • 5.D.1.1: The student is able to make qualitative predictions about natural phenomena based on conservation of linear momentum and restoration of kinetic energy in elastic collisions. • 5.D.1.4: The student is able to design an experimental test of an application of the principle of the conservation of linear momentum, predict an outcome of the experiment using the principle, analyze data generated by that experiment whose uncertainties are expressed numerically, and evaluate the match between the prediction and the outcome. • 5.D.2.2: The student is able to plan data collection strategies to test the law of conservation of momentum in a two-object collision that is elastic or inelastic and analyze the resulting data graphically. • 5.D.2.4: The student is able to analyze data that verify conservation of momentum in collisions with and without an external friction force.

continued

Table 16.2 (*continued*)

AP Physics C: Mechanics learning objectives	• I.D.2.a: Relate mass, velocity, and linear momentum for a moving object, and calculate the total linear momentum of a system of objects. • I.D.3.a(2): Identify situations in which linear momentum, or a component of the linear momentum vector, is conserved. • I.D.3.a(3): Apply linear momentum conservation to one-dimensional elastic and inelastic collisions and two-dimensional completely inelastic collisions.
Literacy connections (*CCSS ELA*)	• *Reading:* Key ideas and details, craft and structure, integration of knowledge and ideas • *Writing:* Text types and purposes, production and distribution of writing, research to build and present knowledge, range of writing • *Speaking and listening:* Comprehension and collaboration, presentation of knowledge and ideas
Mathematics connections (*CCSS Mathematics*)	• *Mathematical practices:* Reason abstractly and quantitatively, construct viable arguments and critique the reasoning of others, use appropriate tools strategically, attend to precision • *Number and quantity:* Reason quantitatively and use units to solve problems, represent and model with vector quantities, perform operations on vectors • *Algebra:* Interpret the structure of expressions, understand solving equations as a process of reasoning and explain the reasoning, solve equations and inequalities in one variable, represent and solve equations and inequalities graphically • *Functions:* Understand the concept of a function and use function notation, interpret functions that arise in applications in terms of the context, analyze functions using different representations, interpret expressions for functions in terms of the situation they model • *Statistics and probability:* Summarize, represent, and interpret data on two categorical and quantitative variables; understand and evaluate random processes underlying statistical experiments; make inferences and justify conclusions from sample surveys, experiments, and observational studies

Lab Handout

Lab 16. Linear Momentum and Collisions: When Two Objects Collide and Stick Together, How Do the Initial Velocity and Mass of One of the Moving Objects Affect the Velocity of the Two Objects After the Collision?

Introduction

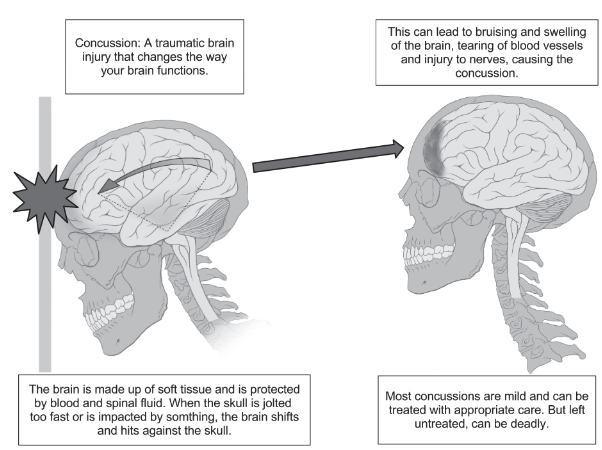
The incidence of traumatic brain injury (TBI) is on the rise in the United States (CDC 2016). At least 1.7 million TBIs occur every year in this country, and these injuries are a contributing factor in about a third (30.5%) of all injury-related deaths (Faul et al. 2010). Adolescents (ages 15–19 years), older adults (ages 65 years and older), and males across all age groups are most likely to sustain a TBI (Faul et al. 2010). A TBI is caused by a bump, blow, or jolt to the head, although not all such events result in a TBI. TBIs can range from mild to severe, but most TBIs are mild and are commonly called concussions (CDC 2016). A single concussion, however, can cause temporary memory loss, confusion, and impaired vision or hearing. It can also cause depression, anxiety, and mood swings. Multiple concussions can make these symptoms permanent.

A concussion is caused when a person's brain hits the inside of the skull. This can occur when a moving person hits a stationary object (like running into a glass door), when a stationary person is hit by a moving object (like a person getting hit in the head by a baseball), or when two people collide with each other (like two people running into each other while playing a sport). As can be seen in Figure L16.1, when the skull is jolted too fast or is impacted by something, the brain shifts and hits against the skull. The "harder" the brain collides with the inside of the skull, the more severe the concussion.

Scientists have shown that the momentum of a collision is related to the severity of a concussion. Consider for example, what happens when a person is hit in the head with a ball. This often happens to softball players, baseball players, and soccer players. When a person is hit in the head by a moving ball, the severity of the concussion will be related to the momentum of that moving ball. Momentum is a function of both the mass of an object and its velocity. As an object accelerates, its

FIGURE L16.1

Movement of the brain during a concussive event



momentum increases. And, for two objects moving at the same velocity, the object with the greater mass will have a greater momentum.

Scientists have been studying collisions between two objects, such as cars, for some time. More and more scientists, however, are now studying the types of collisions that happen during different kinds of sports to better protect athletes from concussions. One type of collision that appears to be related to a high incidence of concussion is tackling in football. Tackling often results in two bodies staying together after the collision; Figure L16.2 shows one example of this. In this example, a defensive player (who is moving) collides with the quarterback (who is stationary). The defensive player holds on to the quarterback after the initial collision so they stay together as they fall to the ground. One goal of this line of research is to determine how the velocity of the moving object (or an athlete) before the collision affects the velocity of the two objects stuck together after the collision. In this investigation, you will have an opportunity to explore this relationship.

FIGURE L16.2

A collision between two football players

Your Task

Use what you know about momentum, collisions, systems, tracking the movement of matter within systems, and the importance of considering issues related to scale, proportion, and quantity to design and carry out an investigation that will allow you to understand what happens when two objects collide and stick together.

The guiding question of this investigation is, ***When two objects collide and stick together, how does the initial velocity and mass of one of the moving objects affect the velocity of the two objects after the collision?***

Materials

You may use any of the following materials during your investigation (some items may not be available):

- Safety glasses or goggles (required)
- 2 Dynamics carts (with Velcro or magnetic bumpers)
- Dynamics track
- Motion detector/sensor and interface
- Video camera
- Computer or tablet with data collection and analysis software and/or video analysis software
- Electronic or triple beam balance
- Cart picket fence
- Mass set
- Stopwatch
- Meterstick or ruler

Safety Precautions

Follow all normal lab safety rules. In addition, take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Wash your hands with soap and water after completing the lab.

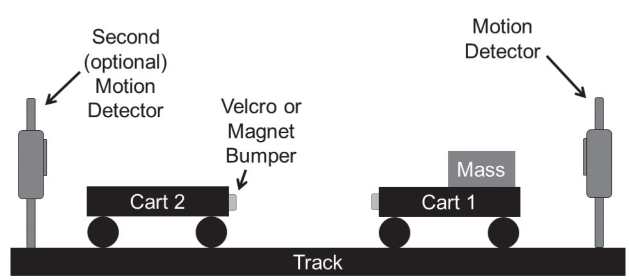
Investigation Proposal Required? ☐ Yes ☐ No

Getting Started

To answer the guiding question, you will need to design and carry out at least two different experiments. First, you will need to determine how changing the initial velocity of a moving object affects the velocity of the two objects after the collision. Next, you will need to determine how changing the mass of the moving object affects the velocity of the two objects after the collision. Figure L16.3 shows how you can use motion detectors/sensors to measure the velocity of a moving object (in this case, a dynamics cart) before and after a collision. The velocity of the moving object can also be measured by using a video camera and video analysis software. Before you can design your two experiments, however, you must determine what type of data you need to collect, how you will collect it, and how you will analyze it.

FIGURE L16.3

One way to measure the velocity of a moving object before and after a collision



To determine *what type of data you need to collect,* think about the following questions:

- What are the boundaries and components of the system you are studying?
- How do components of the system under study interact?
- How will you track the movement of matter within this system?
- How could you keep track of changes in this system quantitatively?
- What factors affects the momentum of an object?
- How will you determine the velocity of each object?
- What will be the independent variable and the dependent variable for each experiment?

To determine *how you will collect the data,* think about the following questions:

- What other factors will you need to control or measure during each experiment?
- Which quantities are vectors, and which quantities are scalars?
- For any vector quantities, which directions are positive and which directions are negative?
- What scale or scales should you use to take your measurements?
- What equipment will you need to collect the measurements you need?
- How will you make sure that your data are of high quality (i.e., how will you reduce error)?
- How will you keep track of and organize the data you collect?

To determine *how you will analyze the data,* think about the following questions:

- What type of calculations will you need to do?
- What types of patterns might you look for as you analyze your data?
- Are there any proportional relationships you can identify?
- What types of comparisons will be useful to make?
- What type of table or graph could you create to help make sense of your data?

Connections to the Nature of Scientific Knowledge and Scientific Inquiry

As you work through your investigation, you may want to consider

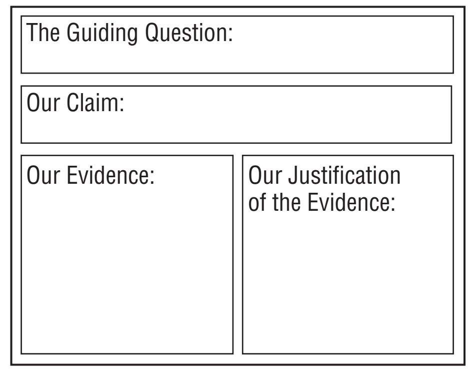
- the difference between observations and inferences in science, and
- how the culture of science, societal needs, and current events influence the work of scientists.

Initial Argument

Once your group has finished collecting and analyzing your data, your group will need to develop an initial argument. Your initial argument needs to include a claim, evidence to support your claim, and a justification of the evidence. The *claim* is your group's answer to the guiding question. The *evidence* is an analysis and interpretation of your data. Finally, the *justification* of the evidence is why your group thinks the evidence matters. The justification of the evidence is important because scientists can use different kinds of evidence to support their claims. Your group will create your initial argument on a whiteboard. Your whiteboard should include all the information shown in Figure L16.4.

FIGURE L16.4

Argument presentation on a whiteboard



Argumentation Session

The argumentation session allows all of the groups to share their arguments. One or two members of each group will stay at the lab station to share that group's argument, while the other members of the group go to the other lab stations to listen to and critique the other arguments. This is similar to what scientists do when they propose, support, evaluate, and refine new ideas during a poster session at a conference. If you are presenting your group's argument, your goal is to share your ideas and answer questions. You should also keep a record of the critiques and suggestions made by your classmates so you can use this feedback to make your initial argument stronger. You can keep track of specific critiques and suggestions for improvement that your classmates mention in the space below.

Critiques about our initial argument and suggestions for improvement:

If you are critiquing your classmates' arguments, your goal is to look for mistakes in their arguments and offer suggestions for improvement so these mistakes can be fixed. You should look for ways to make your initial argument stronger by looking for things that the other groups did well. You can keep track of interesting ideas that you see and hear during the argumentation in the space below. You can also use this space to keep track of any questions that you will need to discuss with your team.

Interesting ideas from other groups or questions to take back to my group:

Once the argumentation session is complete, you will have a chance to meet with your group and revise your initial argument. Your group might need to gather more data or design a way to test one or more alternative claims as part of this process. Remember, your goal at this stage of the investigation is to develop the best argument possible.

Report

Once you have completed your research, you will need to prepare an *investigation report* that consists of three sections. Each section should provide an answer to the following questions:

1. What question were you trying to answer and why?
2. What did you do to answer your question and why?
3. What is your argument?

Your report should answer these questions in two pages or less. This report must be typed, and any diagrams, figures, or tables should be embedded into the document. Be sure to write in a persuasive style; you are trying to convince others that your claim is acceptable or valid!

References

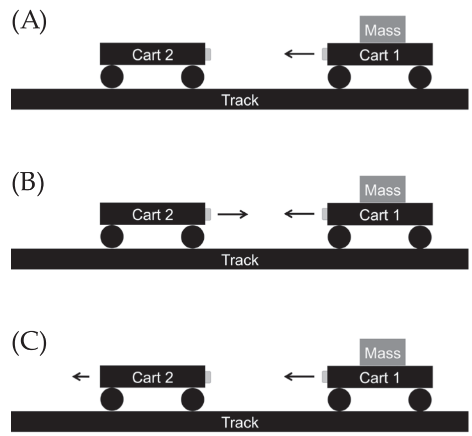
Centers for Disease Control and Prevention. 2016. TBI: Get the facts. *www.cdc.gov/traumaticbraininjury/get_the_facts.html.*

Faul, M., L. Xu, M. M. Wald, and V. G. Coronado. 2010. Traumatic brain injury in the United States: Emergency department visits, hospitalizations and deaths. Atlanta, GA: Centers for Disease Control and Prevention, National Center for Injury Prevention and Control.

Checkout Questions

Lab 16. Linear Momentum and Collisions: When Two Objects Collide and Stick Together, How Do the Initial Velocity and Mass of One of the Moving Objects Affect the Velocity of the Two Objects After the Collision?

The images below show the motion of two carts on a track before they collide with each other. Assume that both carts stick together after the collision. Use this information to answer questions 1 and 2.



1. How would the magnitude of the velocity of the carts after the collision in situation A compare with the magnitude of the velocity of the carts after the collision in situation B? For situation B, assume the magnitude of the velocity for cart 1 equals the magnitude of the velocity for cart 2.

   a. The velocity will be greater in A than in B.
   b. The velocity will be less in A than in B.
   c. The velocity will be equal in A and B.

   How do you know?

2. How would the magnitude of the velocity of the carts after the collision in situation A compare with the magnitude of the velocity of the carts after the collision in situation C? For situation C, assume the magnitude of the velocity for cart 1 is greater than the magnitude of the velocity for cart 2.

   a. The velocity will be greater in A than in C.
   b. The velocity will be less in A than in C.
   c. The velocity will be equal in A and C.

How do you know?

3. The mass of the carts did not change while they were moving during your investigation. Are there instances where the mass of a moving object changes as it moves?

   a. Yes
   b. No

   Explain your answer using an example.

4. How does decreasing the mass of a moving object as it moves affect the momentum of that object?

   a. It decreases the momentum of the object.
   b. It increases the momentum of the object.
   c. It has no effect on the momentum of the object.

   How do you know?

5. In science, there is a difference between inferences and observations.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about linear momentum and collisions.

6. Scientists share a set of values, norms, and commitments that shape what counts as knowing, how to represent or communicate information, and how to interact with other scientists.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about linear momentum and collisions.

7. Scientists often need to need to define the system under study as part of the investigation. Explain why this is useful to do, using an example from your investigation about linear momentum and collisions.

8. Scientists often need to track how matter moves within a system. Explain why this is useful to do, using an example from your investigation about linear momentum and collisions.

9. Scientists often focus on proportional relationships. Explain what a proportional relationship is and why these relationships are useful, using an example from your investigation about linear momentum and collisions.

Teacher Notes

Lab 17. Impulse and Momentum: How Does Changing the Magnitude and Duration of a Force Acting on an Object Affect the Momentum of That Object?

Purpose

The purpose of this lab is to *introduce* students to the core idea of forces and motion, part of the disciplinary core idea (DCI) of Motion and Stability: Forces and Interactions from the *NGSS,* by giving students an opportunity to explore impulses and momentum. This lab also gives students an opportunity to learn about the crosscutting concepts (CCs) of (a) Scale, Proportion, and Quantity; and (b) Energy and Matter: Flows, Cycles, and Conservation from the *NGSS.* In addition, this lab can be used to help students understand three big ideas from AP Physics: (a) the interactions of an object with other objects can be described by forces, (b) interactions between systems can result in changes in those systems, and (c) changes that occur as result of interactions are constrained by conservation laws. As part of the explicit and reflective discussion, students will also learn about (a) the difference between laws and theories in science and (b) the difference between data and evidence in science.

Underlying Physics Concepts

When a force, $\mathbf{F}$, is applied to an object, it acts for some time, Δt. The product, $\mathbf{F}\Delta t$, is defined as an *impulse*, $\mathbf{J}$, in Equation 17.1. In SI units, force is measured in newtons (N), time in seconds (s), and impulse in newton seconds (N·s).

$$\textbf{(Equation 17.1)}\quad \mathbf{J} = \mathbf{F}\Delta t$$

As we know from Newton's second law, an unbalanced force causes an object to accelerate. An impulse can cause a change in an object's momentum, as shown in Equation 17.2, where $\mathbf{J}$ is impulse and $\mathbf{p}$ is momentum (we use $\mathbf{p}$ for momentum because m is already used for mass). In SI units, momentum is measured in kilogram-meters per second (kg·m/s).

$$\textbf{(Equation 17.2)}\quad \mathbf{J} = \Delta\mathbf{p}$$

An object's momentum is equal to the product of its mass, m, and velocity, $\mathbf{v}$, as shown in Equation 17.3. In SI units, mass is measured in kilograms (kg) and velocity is measured in meters per second (m/s).

$$\textbf{(Equation 17.3)}\quad \mathbf{p} = m\mathbf{v}$$

Taken together, Equations 17.2 and 17.3 imply that, for an object of constant mass, an impulse has the effect of changing the velocity. We can combine Equations 17.1, 17.2, and 17.3 to write an equation in terms of observable quantities, shown in Equation 17.4.

$$\textbf{(Equation 17.4)} \quad \mathbf{F}\Delta t = m\Delta \mathbf{v}$$

Dividing both sides by Δt will yield the familiar version of Newton's second law (i.e., $\mathbf{F} = m\mathbf{a}$), though something similar to Equation 17.4 was how Newton actually presented the second law in his famous work *Principia Mathematica* (1687). That is, instead of saying that a force will cause an object to accelerate, Newton's description of his second law is more accurately translated from Latin as stating that the change in momentum of a body is proportional to the impulse acting on the body.

Note that impulse and momentum are vector quantities. As such, the direction of an impulse causes a momentum change in the same direction (see Equation 17.2). Equation 17.4 illustrates this more clearly by showing that the direction of the velocity's *change* comes from the direction of the force applied. Therefore, a force directed to the left can cause an increase in leftward velocity (i.e., increase in momentum) *or* a decrease in rightward velocity (i.e., decreased momentum).

In this investigation, students must determine the effect of increased force on the change in the momentum of the object and the effect of a longer duration of an applied force on the momentum of an object. Assuming that the initial momentum and the force are in the same direction, then an increased force will cause a larger change in momentum over a constant amount of time. And, if the force is held constant, a longer duration will lead to a greater change in momentum.

Timeline

The instructional time needed to complete this lab investigation is 200–280 minutes. Appendix 3 (p. 531) provides options for implementing this lab investigation over several class periods. Option E (280 minutes) should be used if students are unfamiliar with scientific writing, because this option provides extra instructional time for scaffolding the writing process. You can scaffold the writing process by modeling, providing examples, and providing hints as students write each section of the report. Option E can also be used if students are unfamiliar with any of the data collection and analysis tools. Option F (200 minutes) should be used if students are familiar with scientific writing and have developed the skills needed to write an investigation report on their own. In option F, students complete stage 6 (writing the investigation report) and stage 8 (revising the investigation report) as homework.

LAB 17

Materials and Preparation

The materials needed to implement this investigation are listed in Table 17.1. The items can be purchased from a science supply company such as Carolina, Flinn Scientific, PASCO, Vernier, or Ward's Science. The data collection and analysis software and/or the video analysis software) can be purchased from Vernier (Logger *Pro*) or PASCO (SPARKvue or Capstone). These companies also have apps that can be used on Apple- or Android-based tablets and cell phones. We recommend consulting with your school's information technology coordinator to determine the best option for your students.

TABLE 17.1

Materials list for Lab 17

Item	Quantity
• Safety glasses or goggles	1 per student
• Dynamics cart	1 per group
• Fan attachment for cart, with variable speed and duration settings	1 per group
• Dynamics track	1 per group
• Motion detector/sensor	1 per group
• Interface for motion detector/sensor (if used)	1 per group
• Video camera	1 per group
• Computer or tablet with data collection and analysis software (for use with motion detector/sensor) or video analysis software (for use with video camera)	1 per group
• Electronic or triple beam balance	1 per group
• Stopwatch	1 per group
• Meterstick or ruler	1 per group
• Investigation Proposal C (optional)	2 per group
• Whiteboard, 2' × 3'*	1 per group
• Lab Handout	1 per student
• Peer-review guide and teacher scoring rubric	1 per student
• Checkout Questions	1 per student

* As an alternative, students can use computer and presentation software such as Microsoft PowerPoint or Apple Keynote to create their arguments.

Be sure to use a set routine for distributing and collecting the materials during the lab investigation. One option is to set up the materials for each group at each group's lab station before class begins. This option works well when there is a dedicated section of the classroom for lab work and the materials are large and difficult to move (such as a dynamics track). A second option is to have all the materials on a table or cart at a central location. You can then assign a member of each group to be the "materials manager." This individual is responsible for collecting all the materials his or her group needs from the table or cart during class and for returning all the materials at the end of the class. This option works well when the materials are small and easy to move (such as stopwatches, metersticks, or hanging masses). It also makes it easy to inventory the materials at the end of the class before students leave for the day.

Safety Precautions

Remind students to follow all normal lab safety rules. In addition, tell students to take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Wash hands with soap and water after completing the lab.

Topics for the Explicit and Reflective Discussion

Reflecting on the Use of Core Ideas and Crosscutting Concepts During the Investigation

Teachers should begin the explicit and reflective discussion by asking students to discuss what they know about the core idea they used during the investigation. The following are some important concepts related to the core idea of forces and motion that students will need to explain how the momentum of an object will change in response to an impulse:

- A reference frame is needed to determine the direction and the magnitude of the displacement, velocity, and acceleration of an object.
- Force is considered a vector quantity because a force has both magnitude and direction.
- A *system* is an object or a collection of objects. An object is treated as if it has no internal structure.
- The boundary between a system and its environment is a decision made by the person considering the situation in order to simplify or otherwise assist in analysis.
- An *impulse* is the product of the average force acting on an object and the time interval during which the interaction occurred.

To help students reflect on what they know about forces and motion, we recommend showing them two or three images using presentation software that help illustrate these important ideas. You can then ask the students the following questions to encourage them to share how they are thinking about these important concepts:

1. What do we see going on in this image?
2. Does anyone have anything else to add?
3. What might be going on that we can't see?
4. What are some things that we are not sure about here?

You can then encourage students to think about how CCs played a role in their investigation. There are at least two CCs that students need to explain how the momentum of an object will change in response to an impulse: (a) Scale, Proportion, and Quantity; and (b) Energy and Matter: Flows, Cycles, and Conservation (see Appendix 2 [p. 527] for a brief description of these CCs). To help students reflect on what they know about these CCs, we recommend asking them the following questions:

1. Why is it important to keep track of changes in a system quantitatively during an investigation?
2. What did you keep track of quantitatively during your investigation? What did that allow you to do?
3. Scientists often attempt to track how energy and matter move into, out of, and within systems as part of an investigation. Why is this useful?
4. How did you attempt to track how matter moves within the system you were studying? What did tracking the movement of matter allow you to do during your investigation?

You can then encourage the students to think about how they used all these different concepts to help answer the guiding question and why it is important to use these ideas to help justify their evidence for their final arguments. Be sure to remind your students to explain why they included the evidence in their arguments and make the assumptions underlying their analysis and interpretation of the data explicit in order to provide an adequate justification of their evidence.

Reflecting on Ways to Design Better Investigations

It is important for students to reflect on the strengths and weaknesses of the investigation they designed during the explicit and reflective discussion. Students should therefore be encouraged to discuss ways to eliminate potential flaws, measurement errors, or sources of uncertainty in their investigations. To help students be more reflective about the design of their investigation and what they can do to make their investigations more rigorous in the future, you can ask them the following questions:

1. What were some of the strengths of the way you planned and carried out your investigation? In other words, what made it scientific?
2. What were some of the weaknesses of the way you planned and carried out your investigation? In other words, what made it less scientific?
3. What rules can we make, as a class, to ensure that our next investigation is more scientific?

Reflecting on the Nature of Scientific Knowledge and Scientific Inquiry

This investigation can be used to illustrate two important concepts related to the nature of scientific knowledge and the nature of scientific inquiry: (a) the difference between laws and theories in science and (b) the difference between data and evidence in science (see Appendix 2 for a brief description of these two concepts. Be sure to review these concepts during and at the end of the explicit and reflective discussion. To help students think about these concepts in relation to what they did during the lab, you can ask them the following questions:

1. Laws and theories are different in science. Is $\mathbf{F}\Delta t = m\Delta\mathbf{v}$ an example of a theory or a law? Why?
2. Can you work with your group to come up with a rule that you can use to decide if something is a theory or a law? Be ready to share in a few minutes.
3. You had to talk about data and evidence during your investigation. Can you give me some examples of data and evidence from your investigation?
4. Can you work with your group to come up with a rule that you can use to decide if a piece of information is data or evidence? Be ready to share in a few minutes.

You can also use presentation software or other techniques to encourage your students to think about these concepts. You can show examples of either a law (such as $\mathbf{g} = GM/\mathbf{r}^2$) or a theory (such as *gravity is the curvature of four-dimensional space-time due to the presence of mass*) and ask students to indicate if they think it is a law or a theory and why. You can also show examples of information from the investigation that are either data or evidence and ask students to classify each example and explain their thinking.

Be sure to remind your students that, to be proficient in science, it is important that they understand what counts as scientific knowledge and how that knowledge develops over time.

Hints for Implementing the Lab

- Allowing students to design their own procedures for collecting data gives students an opportunity to try, to fail, and to learn from their mistakes. However, you can scaffold students as they develop their procedure by having them fill out an investigation proposal. These proposals provide a way for you to offer students hints and suggestions without telling them how to do it. You can also check the proposals quickly during a class period. We recommend having them fill out a proposal for each experiment. For this lab we suggest using Investigation Proposal C.
- We recommend using motion sensors to collect data about the velocity of the carts. However, students can also determine the velocity of the carts by conducting a video analysis of the motion of the carts.
- We recommend using a fan attachment with variable speed and duration settings. This type of fan attachment makes it easier for students to design more informative experiments. The variable duration setting is especially useful.
- Learn how to use the fan attachment and dynamics track before the lab begins. It is important for you to know how to use the equipment so you can help students when technical issues arise.
- Allow students to become familiar with the fan attachment and dynamics track as part of the tool talk before they begin to design their investigation. Giving them 5–10 minutes to examine the available equipment will let them see what they can and cannot do with it. This also gives students a chance to begin thinking about what variables to test and how to control for other variables.
- Be sure to allow students to go back and re-collect data at the end of the argumentation session. Students often realize that they made numerous mistakes when they were collecting data as a result of their discussions during the argumentation session. The students, as a result, will want a chance to re-collect data, and the re-collection of data should be encouraged when time allows. This also offers an opportunity to discuss what scientists do when they realize a mistake is made inside the lab.

If students use a motion detector/sensor

- Learn how to use the motion detector/sensor and the data collection and analysis software before the lab begins. It is important for you to know how to use the equipment and software so you can help students when technical issues arise.
- Allow the students to become familiar with the motion detector/sensor and data collection and analysis software as part of the tool talk before they begin to design

their investigation. Giving them 5–10 minutes to examine the equipment and software will let them see what they can and cannot do with it.

If students use video analysis

- We suggest allowing students to familiarize themselves with the video analysis software before they finalize the procedure for the investigation, especially if they have not used such software previously. This gives students an opportunity to learn how to work with the software and to improve the quality of the video they take.
- Remind students to hold the video camera as still as possible. Any movement of the camera will introduce error into their analysis. If using actual camcorders, we recommend using a tripod to hold the camera steady. If students are using a camera on a cell phone or tablet, we recommend using a table to help steady the camera.
- Remind students to place a meterstick in the same field of view as the motion they are capturing with the video camera. Also, the meterstick should be approximately the same distance from the camera as the motion. Most video analysis software requires the user to define a scale in the video (this allows the software to establish distances and, subsequently, other variables dependent on distance and displacement).

Connections to Standards

Table 17.2 (p. 374) highlights how the investigation can be used to address specific performance expectations from the *NGSS;* learning objectives from AP Physics 1; learning objectives from AP Physics C: Mechanics, *Common Core State Standards,* in English language arts (*CCSS ELA*); and *Common Core State Standards,* Mathematics (*CCSS Mathematics*).

TABLE 17.2

Lab 17 alignment with standards

***NGSS* performance expectation**	• HS-PS2-2: Use mathematical representation to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system.
AP Physics 1 learning objectives	• 3.D.1.1: The student is able to justify the selection of data needed to determine the relationship between the direction of the force acting on an object and the change in momentum caused by that force. • 3.D.2.1: The student is able to justify the selection of routines for the calculation of the relationships between changes in momentum of an object, average force, impulse, and time of interaction. • 3.D.2.2: The student is able to predict the change in momentum of an object from the average force exerted on the object and the interval of time during which the force is exerted. • 3.D.2.3: The student is able to analyze data to characterize the change in momentum of an object from the average force exerted on the object and the interval of time during which the force is exerted. • 3.D.2.4: The student is able to design a plan for collecting data to investigate the relationship between changes in momentum and the average force exerted on an object over time.
AP Physics C: Mechanics learning objectives	• I.D.2.a: Relate mass, velocity, and linear momentum for a moving object, and calculate the total linear momentum of a system of objects. • I.D.2.b: Relate impulse to the change in linear momentum and the average force acting on an object. • I.D.2.e: Calculate the change in momentum of an object given a function $\mathbf{F}(t)$ for the net force acting on the object.
Literacy connections (*CCSS ELA*)	• *Reading:* Key ideas and details, craft and structure, integration of knowledge and ideas • *Writing:* Text types and purposes, production and distribution of writing, research to build and present knowledge, range of writing • *Speaking and listening:* Comprehension and collaboration, presentation of knowledge and ideas

Mathematics connections (*CCSS Mathematics*)	• *Mathematical practices:* Reason abstractly and quantitatively, construct viable arguments and critique the reasoning of others, use appropriate tools strategically, attend to precision • *Number and quantity:* Reason quantitatively and use units to solve problems, represent and model with vector quantities, perform operations on vectors • *Algebra:* Interpret the structure of expressions, understand solving equations as a process of reasoning and explain the reasoning, solve equations and inequalities in one variable, represent and solve equations and inequalities graphically • *Functions:* Understand the concept of a function and use function notation, interpret functions that arise in applications in terms of the context, analyze functions using different representations, interpret expressions for functions in terms of the situation they model • *Statistics and probability:* Summarize, represent, and interpret data on two categorical and quantitative variables; understand and evaluate random processes underlying statistical experiments; make inferences and justify conclusions from sample surveys, experiments, and observational studies

Reference

Newton, I. 1687. *Philosophiae naturalis principia mathematica* [Mathematical principles of natural philosophy]. London: S. Pepys.

Lab Handout

Lab 17. Impulse and Momentum: How Does Changing the Magnitude and Duration of a Force Acting on an Object Affect the Momentum of That Object?

Introduction

Forces are responsible for all changes in motion and momentum. Regardless of how quickly a force is applied, it can still change the motion of an object. Consider what happens when someone hits a ball with a bat. The time that the bat and ball are in contact is very short, but the force from this collision is strong enough to significantly change the motion of a ball. The force that results from a bat hitting a ball can even be strong enough to change the shape of the ball (see Figure L17.1) or the bat (see Figure L17.2).

FIGURE L17.1

A ball deforming from the force that results from the collision of the bat and the ball

FIGURE L17.2

The bat breaking from the force that results from the collision of the bat and the ball

Momentum is defined as the mass of an object multiplied by its velocity. Momentum is a vector quantity because it has both a magnitude and a direction. As a result, the momentum of an object can be positive or negative, depending on the direction an object is moving. Force is also a vector quantity because forces have both a magnitude and a direction. When an unbalanced force acts on an object, the momentum of that object will change. In other words, an unbalanced force will change the momentum of an object.

The amount of time that an unbalanced force acts on an object is also important to consider when examining the change in momentum of an object. Sometimes the amount of time a force is applied to an object is very short, such as when a bat hits a ball, and other times it is applied over long periods, such as when the thrusters attached to a satellite are fired for several minutes to launch that satellite into orbit. The term *impulse* is used to describe the product of the magnitude and the duration of a force that acts on an object. In this investigation you will have an opportunity to examine how the nature of an impulse can change the momentum of a cart moving in one dimension. Your goal is to create a conceptual model that you can use to explain how the magnitude and duration of a force affects the change in momentum of a cart.

Your Task

Use what you know about momentum, impulse, the movement of matter within a system, and scale, proportional relationships, and quantity to develop a conceptual model that will enable you to explain how the momentum of an object will change in response to an impulse. To develop this conceptual model, you will need to design and carry out two different experiments to determine how (a) the magnitude of a force affects the momentum of an object and (b) the duration of a force affects the momentum of an object. Once you have developed your model, you will need to test it to determine if allows you to make accurate predictions about the change of momentum of an object over time in response to different types of impulse.

The guiding question of this investigation is, ***How does changing the magnitude and the duration of a force acting on an object affect the momentum of that object?***

Materials

You may use any of the following materials during your investigation (some items may not be available):

- Safety glasses or goggles (required)
- Dynamics cart with fan attachment
- Dynamics track
- Motion detector/sensor and interface
- Video camera
- Computer or tablet with data collection and analysis software and/or video analysis software
- Electronic or triple beam balance
- Stopwatch
- Meterstick or ruler

Safety Precautions

Follow all normal lab safety rules. In addition, take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.

2. Keep fingers and toes out of the way of the moving objects.
3. Wash hands with soap and water after completing the lab.

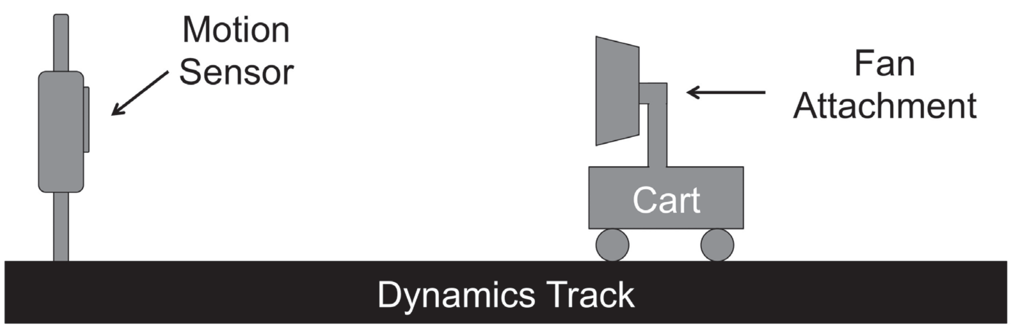
Investigation Proposal Required? ☐ Yes ☐ No

Getting Started

The first step in developing your conceptual model is to design and carry out two experiments. In the first experiment, you will need to determine how changing the magnitude of a force will affect the momentum of a cart. In the second experiment, you will need to determine how changing the duration of the force affects the momentum of a cart. Figure L17.3 illustrates how you can use the available equipment to study the momentum of cart moving in one dimension. Before you can design your experiments, however, you must determine what type of data you need to collect, how you will collect it, and how you will analyze it.

FIGURE L17.3

One way to study the change in momentum of an object



To determine *what type of data you need to collect,* think about the following questions:

- What are the boundaries and components of the system you are studying?
- How do components of the system under study interact?
- How will you track the movement of matter within this system?
- How could you keep track of changes in this system quantitatively?
- What factors affects the momentum of an object?
- How will you determine the velocity of each object?
- What will be the independent variable and the dependent variable for each experiment?

To determine *how you will collect the data,* think about the following questions:

- What other factors will you need to control or measure during each experiment?
- Which quantities are vectors, and which quantities are scalars?
- For any vector quantities, which directions are positive and which directions are negative?
- What scale or scales should you use when you take your measurements?
- What equipment will you need to collect the measurements you need?
- How will you make sure that your data are of high quality (i.e., how will you reduce error)?
- How will you keep track of and organize the data you collect?

To determine *how you will analyze the data,* think about the following questions:

- What type of calculations will you need to do?
- What types of patterns might you look for as you analyze your data?
- Are there any proportional relationships you can identify?
- What types of comparisons will be useful to make?
- What type of table or graph could you create to help make sense of your data?

Once you have determined how the magnitude of a force and the duration of a force affect the momentum of a cart in one dimension, your group will need to develop a conceptual model. Your model must include the various forces acting on the cart and allow you to make accurate predictions about how the momentum of cart changes over time in response to different forces.

The last step in this investigation will be to test your model. To accomplish this goal, you can apply different impulses (ones that you did not test) to the cart to determine if your model enables you to make accurate predictions about how the momentum of the cart changes over time. If you are able to use your model to make accurate predictions, then you will be able to generate the evidence you need to convince others that your model is a valid and acceptable. The fan attached to the cart you will use in this investigation may have a limited number of different speeds, so it will be important to reserve at least one speed setting for this step of your investigation.

Connections to the Nature of Scientific Knowledge and Scientific Inquiry

As you work through your investigation, you may want to consider

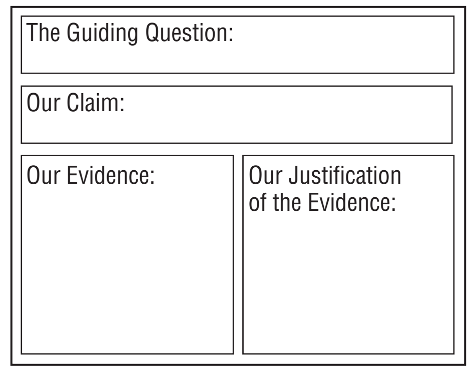
- the difference between laws and theories in science, and
- the difference between data and evidence in science.

Initial Argument

Once your group has finished collecting and analyzing your data, your group will need to develop an initial argument. Your initial argument needs to include a claim, evidence to support your claim, and a justification of the evidence. The *claim* is your group's answer to the guiding question. The *evidence* is an analysis and interpretation of your data. Finally, the *justification* of the evidence is why your group thinks the evidence matters. The justification of the evidence is important because scientists can use different kinds of evidence to support their claims. Your group will create your initial argument on a whiteboard. Your whiteboard should include all the information shown in Figure L17.4.

FIGURE L17.4

Argument presentation on a whiteboard



Argumentation Session

The argumentation session allows all of the groups to share their arguments. One or two members of each group will stay at the lab station to share that group's argument, while the other members of the group go to the other lab stations to listen to and critique the other arguments. This is similar to what scientists do when they propose, support, evaluate, and refine new ideas during a poster session at a conference. If you are presenting your group's argument, your goal is to share your ideas and answer questions. You should also keep a record of the critiques and suggestions made by your classmates so you can use this feedback to make your initial argument stronger. You can keep track of specific critiques and suggestions for improvement that your classmates mention in the space below.

Critiques about our initial argument and suggestions for improvement:

If you are critiquing your classmates' arguments, your goal is to look for mistakes in their arguments and offer suggestions for improvement so these mistakes can be fixed. You should look for ways to make your initial argument stronger by looking for things that the other groups did well. You can keep track of interesting ideas that you see and hear during the argumentation in the space below. You can also use this space to keep track of any questions that you will need to discuss with your team.

Interesting ideas from other groups or questions to take back to my group:

Once the argumentation session is complete, you will have a chance to meet with your group and revise your initial argument. Your group might need to gather more data or design a way to test one or more alternative claims as part of this process. Remember, your goal at this stage of the investigation is to develop the best argument possible.

Report

Once you have completed your research, you will need to prepare an *investigation report* that consists of three sections. Each section should provide an answer to the following questions:

1. What question were you trying to answer and why?
2. What did you do to answer your question and why?
3. What is your argument?

Your report should answer these questions in two pages or less. This report must be typed, and any diagrams, figures, or tables should be embedded into the document. Be sure to write in a persuasive style; you are trying to convince others that your claim is acceptable or valid!

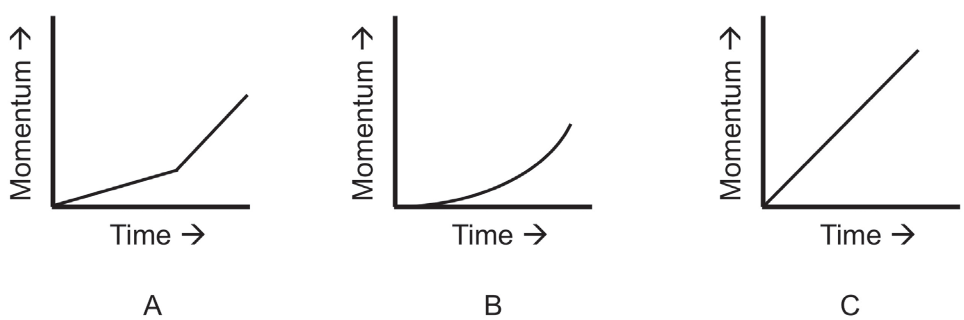
Checkout Questions

Lab 17. Impulse and Momentum: How Does Changing the Magnitude and Duration of a Force Acting on an Object Affect the Momentum of That Object?

1. How can the shape of a force versus time graph be used to determine an object's momentum?

Use the following information to answer questions 2–4. Consider a cart starting from rest with a fan attachment that applies a constant force. Assume that there is no friction acting on the cart as it moves.

2. What would the momentum versus time graph look like if the fan force doubled halfway through the trial?



   a. Graph A
   b. Graph B
   c. Graph C

How do you know?

3. What could cause the slope to become zero?
   a. Doubling the fan force a second time
   b. Turning the fan off
   c. Leaving the fan as is

   How do you know?

4. Draw a momentum versus time graph showing the change in momentum if the fan stayed on for twice as long.

   Why did you draw your momentum versus time graph like that?

5. There is a difference between a scientific law and a scientific theory.
   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about impulse and momentum.

6. There is a difference between data and evidence in science.
    a. I agree with this statement.
    b. I disagree with this statement.

    Explain your answer, using an example from your investigation about impulse and momentum.

7. In physics, it is important to classify something as either a vector quantity or a scalar quantity. Explain what a vector is and why it is important to identify vector quantities in physics, using an example from your investigation about impulse and momentum.

8. Scientists often need to track how energy or matter moves into, out of, or within a system during an investigation. Explain why tracking energy and matter is such an important part of science, using an example from your investigation about impulse and momentum.

Application Labs

Teacher Notes

Lab 18. Elastic and Inelastic Collisions: Which Properties of a System Are Conserved During a Collision?

Purpose

The purpose of this lab is for students to *apply* what they know about the core idea of forces and motion, part of the disciplinary core idea (DCI) of Motion and Stability: Forces and Interactions from the *NGSS,* to determine which properties of a system are conserved in a collision. This lab also gives students an opportunity to learn about the crosscutting concepts (CCs) of (a) Systems and System Models and (b) Energy and Matter: Flows, Cycles, and Conservation from the *NGSS.* In addition, this lab can be used to help students understand three big ideas from AP Physics: (a) the interactions of an object with other objects can be described by forces, (b) interactions between systems can result in changes in those systems, and (c) changes that occur as result of interactions are constrained by conservation laws. As part of the explicit and reflective discussion, students will also learn about (a) the difference between laws and theories in science and (b) the difference between data and evidence in science.

Underlying Physics Concepts

Scientists have identified a number of conservation laws. A conservation law states that some property of an isolated system is the same before and after some specific interaction takes place within that system. Some of the conservation laws that have been identified include conservation of linear momentum, rotational momentum, and total energy within a system. Mathematically, we can represent conservation laws using Equation 18.1, where $\sum$ is "the sum of" and x is a generic symbol for some property of constituent parts of the system; x is the value of the property before the collision and x' is the value of the property after the collision.

$$\textbf{(Equation 18.1)} \quad \sum x = \sum x'$$

If a property is conserved, then it will obey Equation 18.1. In this investigation, the two properties of the system that will be conserved are mass and momentum. Thus, for each property students are testing in this investigation, they are asking if Equation 18.1 holds true for that property when two carts collide.

The law of conservation of mass is expressed in Equations 18.2 and 18.3 relative to the collision between two carts. In Equation 18.2, the law of conservation of mass is shown as the sum of the masses of the two carts before the collision, respectively, will be equal to the sum of the masses of the two carts after the collision. In Equation 18.3, the conservation of mass is shown where each mass is treated separately. In this equation, m_1 is the mass of cart 1 before the collision, m'_1 is the mass of cart 1 after the collision, m_2 is the mass of cart 2 before the collision, and m'_2 is the mass of cart 2 after the collision. In SI units, mass is measured in kilograms (kg).

(Equation 18.2) $\sum m = \sum m'$

(Equation 18.3) $m_1 + m_2 = m'_1 + m'_2$

Equations 18.4 and 18.5 (which is derived from Equation 18.4) show the law of conservation of momentum expressed in slightly different mathematical terms. In Equation 18.4, the law of conservation of momentum is shown as the sum of the momentum of each cart, respectively, before and after the collision, where **p** is used to represent momentum. In Equation 18.5, the law of conservation of momentum is shown with the momentum of each cart treated separately both before and after the collision. In SI units, momentum is measured in kilogram-meters per second (kg·m/s).

(Equation 18.4) $\sum \mathbf{p} = \sum \mathbf{p}'$

(Equation 18.5) $\mathbf{p}_1 + \mathbf{p}_2 = \mathbf{p}'_1 + \mathbf{p}'_2$

Because momentum of an object is the product of the mass of the object times the velocity of the object, we can rewrite Equation 18.5 by substituting in the mass and velocity values for each cart, as shown in Equation 18.6. In this equation, m_1 represents the mass of cart 1 before the collision, $\mathbf{v}_1$ represents the mass of cart 1 before the collision, m'_1 represents the mass of cart 1 after the collision, and $\mathbf{v}'_1$ represents the velocity of cart 1 after the collision. In SI units, velocity is measured in meters per second (m/s).

(Equation 18.6) $m_1\mathbf{v}_1 + m_2\mathbf{v}_2 = m_1\mathbf{v}'_1 + m_2\mathbf{v}'_2$

With regard to the total momentum of the system, it is important to keep in mind the sign conventions for velocity. Traditionally, things in the upward, right, north, or east direction get a positive sign, and things in the downward, left, south, or west direction get a negative sign. For example, in Figure 18.1 (p. 388), the truck moving to the right would have a positive value for velocity. The car moving to the left would have a negative velocity. This means that the total momentum of the system can be smaller in magnitude than the momentum of two constituent parts. For example, if the truck has a mass of 5,000 kg and is moving to the right at 10 m/s and the car has a mass of 2,000 kg and is moving to the left at 20 m/s, then the total momentum of the two-vehicle system before the collision is 10,000 kg·m/s, as shown in Equation 18.7.

(Equation 18.7) *Total momentum* = (5,000 kg · 10 m/s) + (2,000 kg · −20 m/s) = 10,000 kg·m/s

Note that the magnitude of the momentum of the truck is 50,000 kg·m/s and the magnitude of the momentum of the small car is 40,000 kg·m/s. Yet the total momentum of the system is only 10,000 kg·m/s to the right.

FIGURE 18.1

A truck and a car before a collision

Finally, physicists distinguish between elastic and inelastic collisions. In an elastic collision, both momentum and kinetic energy are conserved. In an inelastic collision, only momentum is conserved. Mathematically, an inelastic collision only obeys Equation 18.4, whereas an elastic collision obeys both Equation 18.4 and Equation 18.8, where KE is used to represent the kinetic energy of the system. Equation 18.9 shows the mathematical expression for kinetic energy, where *m* is the mass of an object and **v** is the velocity of the object. In SI units, kinetic energy is measured in joules (J).

(Equation 18.8) $\sum \mathrm{KE} = \sum \mathrm{KE}'$

(Equation 18.9) $\mathrm{KE} = \frac{1}{2}m\mathbf{v}^2$

If we substitute Equation 18.9 into Equation 18.8, we can derive Equation 18.10, which shows the conservation of kinetic energy for an elastic collision.

(Equation 18.10) $\frac{1}{2}m_1\mathbf{v_1}^2 + \frac{1}{2}m_2\mathbf{v_2}^2 = \frac{1}{2}m_1\mathbf{v_1}'^2 + \frac{1}{2}m_2\mathbf{v_2}'^2$

Most collisions that occur on a daily basis are inelastic, where kinetic energy is not conserved. In fact, the only elastic collisions that have been observed are collisions between atoms. This does not mean that inelastic collisions violate the law of conservation of energy, because the law of conservation of energy states that the total energy is conserved, not just the kinetic energy. During a collision, some energy is transformed into sound or heat energy. Finally, some collisions that we can observe (such as two billiard balls colliding) are very close to being elastic, so we often treat them as if they are elastic, while recognizing this is not the case.

Timeline

The instructional time needed to complete this lab investigation is 170–230 minutes. Appendix 3 (p. 531) provides options for implementing this lab investigation over several class periods. Option C (230 minutes) should be used if students are unfamiliar with scientific writing, because this option provides extra instructional time for scaffolding the writing process. You can scaffold the writing process by modeling, providing examples, and providing hints as students write each section of the report. Option C can also be used if students are unfamiliar with any of the data collection and analysis tools. Option D (170 minutes) should be used if students are familiar with scientific writing and have developed the skills needed to write an investigation report on their own. In option D, students complete stage 6 (writing the investigation report) and stage 8 (revising the investigation report) as homework.

Materials and Preparation

The materials needed to implement this investigation are listed in Table 18.1 (p. 390). The items can be purchased from a science supply company such as Carolina, Flinn Scientific, PASCO, Vernier, or Ward's Science. The video analysis software can be purchased from Vernier (Logger *Pro*) or PASCO (SPARKvue or Capstone). These companies also have apps that can be used on Apple- or Android-based tablets and cell phones. We recommend consulting with your school's information technology coordinator to determine the best option for your students.

TABLE 18.1

Materials list for Lab 18

Item	Quantity
Safety glasses or goggles	1 per student
Dynamics carts	2 per group
Dynamics track	1 per group
Bumper kit for the carts (includes hoops, magnets or Velcro, rubber, and clay)	1 per group
Video camera	1 per group
Computer or tablet with video analysis software	1 per group
Electronic or triple beam balance	1 per group
Mass set	1 per group
Stopwatches	2–3 per group
Ruler	1 per student
Whiteboard, 2' × 3'*	1 per group
Lab Handout	1 per student
Investigation Proposal B (optional)	2 per group
Peer-review guide and teacher scoring rubric	1 per student
Checkout Questions	1 per student

* As an alternative, students can use computer and presentation software such as Microsoft PowerPoint or Apple Keynote to create their arguments.

Be sure to use a set routine for distributing and collecting the materials during the lab investigation. One option is to set up the materials for each group at each group's lab station before class begins. This option works well when there is a dedicated section of the classroom for lab work and the materials are large and difficult to move (such as a dynamics track). A second option is to have all the materials on a table or cart at a central location. You can then assign a member of each group to be the "materials manager." This individual is responsible for collecting all the materials his or her group needs from the table or cart during class and for returning all the materials at the end of the class. This option works well when the materials are small and easy to move (such as stopwatches, metersticks, or hanging masses). It also makes it easy to inventory the materials at the end of the class before students leave for the day.

Safety Precautions

Remind students to follow all normal lab safety rules. In addition, tell students to take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Wash hands with soap and water after completing the lab.

Topics for the Explicit and Reflective Discussion

Reflecting on the Use of Core Ideas and Crosscutting Concepts During the Investigation

Teachers should begin the explicit and reflective discussion by asking students to discuss what they know about the core idea they used during the investigation. The following are some important concepts related to the core idea of forces and motion that students will need to determine which properties of a system are conserved during a collision:

- A reference frame is needed to determine the direction and the magnitude of the displacement, velocity, and acceleration of an object.
- Force is considered a vector quantity because a force has both magnitude and direction.
- A *system* is an object or a collection of objects. An object is treated as if it has no internal structure.
- The boundary between a system and its environment is a decision made by the person considering the situation in order to simplify or otherwise assist in analysis.
- Conserved quantities are constant in an isolated or a closed system. An open system is one that exchanges any conserved quantity with its surroundings.
- Linear momentum is conserved in all systems.
- The change in momentum of an object occurs over a time interval.
- The force that one object exerts on a second object changes the momentum of the second object (in the absence of other forces on the second object).

To help students reflect on what they know about forces and motion, we recommend showing them two or three images using presentation software that help illustrate these important ideas. You can then ask the students the following questions to encourage them to share how they are thinking about these important concepts:

1. What do we see going on in this image?

2. Does anyone have anything else to add?
3. What might be going on that we can't see?
4. What are some things that we are not sure about here?

You can then encourage students to think about how CCs played a role in their investigation. There are at least two CCs that students need to determine which properties of a system are conserved during a collision: (a) Systems and System Models and (b) Energy and Matter: Flows, Cycles, and Conservation (see Appendix 2 [p.527] for a brief description of these CCs). To help students reflect on what they know about these CCs, we recommend asking them the following questions:

1. Scientists often need to define the system under study and then make a model during an investigation. Why is developing a model of system so useful in science?
2. What were the boundaries and components of the system you studied during this investigation? What were the strengths and limitations of the model you developed?
3. Scientists often attempt to track how energy and matter move into, out of, and within systems as part of an investigation. Why is this useful?
4. How did you attempt to track how matter moves within the system you were studying? What did tracking the movement of matter allow you to do during your investigation?

You can then encourage the students to think about how they used all these different concepts to help answer the guiding question and why it is important to use these ideas to help justify their evidence for their final arguments. Be sure to remind your students to explain why they included the evidence in their arguments and make the assumptions underlying their analysis and interpretation of the data explicit in order to provide an adequate justification of their evidence.

Reflecting on Ways to Design Better Investigations

It is important for students to reflect on the strengths and weaknesses of the investigation they designed during the explicit and reflective discussion. Students should therefore be encouraged to discuss ways to eliminate potential flaws, measurement errors, or sources of uncertainty in their investigations. To help students be more reflective about the design of their investigation and what they can do to make their investigations more rigorous in the future, you can ask them the following questions:

1. What were some of the strengths of the way you planned and carried out your investigation? In other words, what made it scientific?

2. What were some of the weaknesses of the way you planned and carried out your investigation? In other words, what made it less scientific?
3. What rules can we make, as a class, to ensure that our next investigation is more scientific?

Reflecting on the Nature of Scientific Knowledge and Scientific Inquiry

This investigation can be used to illustrate two important concepts related to the nature of scientific knowledge and the nature of scientific inquiry: (a) the difference between laws and theories in science and (b) the difference between data and evidence in science (see Appendix 2 for a brief description of these two concepts). Be sure to review these concepts during and at the end of the explicit and reflective discussion. To help students think about these concepts in relation to what they did during the lab, you can ask them the following questions:

1. Laws and theories are different in science. Is $\mathbf{F}\,\Delta t = m\Delta\mathbf{v}$ an example of a theory or a law? Why?
2. Can you work with your group to come up with a rule that you can use to decide if something is a law or a theory? Be ready to share in a few minutes.
3. You had to talk about data and evidence during your investigation. Can you give me some examples of data and evidence from your investigation?
4. Can you work with your group to come up with a rule that you can use to decide if a piece of information is data or evidence? Be ready to share in a few minutes.

You can also use presentation software or other techniques to encourage your students to think about these concepts. You can show examples of either a law (such as $\mathbf{g} = GM/\mathbf{r}^2$) or a theory (such as *gravity is the curvature of four-dimensional space-time due to the presence of mass*) and ask students to indicate if they think it is a law or a theory and why. You can also show examples of information from the investigation that are either data or evidence and ask students to classify each example and explain their thinking.

Be sure to remind your students that, to be proficient in science, it is important that they understand what counts as scientific knowledge and how that knowledge develops over time.

Hints for Implementing the Lab

- This investigation can be used at several points during the year. You can use this investigation after introducing momentum but before introducing the law of conservation of momentum. You can also use it after teaching about conservation of momentum but before introducing the concept of elastic and inelastic collisions. If you choose to use this investigation after introducing momentum but before introducing the law of conservation of momentum, we suggest not discussing energy during the explicit and reflective discussion. Finally, you can use this lab after teaching about momentum and energy but before teaching about elastic and inelastic collisions.

- Allowing students to design their own procedures for collecting data gives students an opportunity to try, to fail, and to learn from their mistakes. However, you can scaffold students as they develop their procedure by having them fill out an investigation proposal. These proposals provide a way for you to offer students hints and suggestions without telling them how to do it. You can also check the proposals quickly during a class period. We recommend that students fill out a proposal for each experiment they design. For this lab we suggest using Investigation Proposal B.
- Be sure to remind students to use different types of bumpers on the cart to model different types of collisions. Bumper kits for carts usually include hoops, Velcro or magnets, rubber, and clay.
- Learn how to use the dynamics cart and track, the bumper kit, and the video analysis software before the lab begins. It is important for you to know how to use the equipment so you can help students when technical issues arise.
- Allow the students to become familiar with the dynamics cart and track, the bumper kit, and the video analysis software as part of the tool talk before they begin to design their investigation. Giving them 5–10 minutes to examine the equipment and materials will let them see what they can and cannot do with them. This also gives students a chance to begin thinking about what variables to test and how to control for other variables.
- Remind students to hold the video camera as still as possible. Any movement of the camera will introduce error into their analysis. If using actual camcorders, we recommend using a tripod to hold the camera steady. If students are using a camera on a cell phone or tablet, we recommend using a table to help steady the camera.
- Remind students to place a meterstick in the same field of view as the motion they are capturing with the video camera. Also, the meterstick should be approximately the same distance from the camera as the motion. Most video analysis software requires the user to define a scale in the video (this allows the software to establish distances and, subsequently, other variables dependent on distance and displacement).
- During this lab, students may falsify a conservation law for velocity, acceleration, and force. That is, the data will show that these quantities are not conserved. This is an important finding, and we recommend that you suggest to students that they make these findings part of their argument.

- Be sure to allow students to go back and re-collect data at the end of the argumentation session. Students often realize that they made numerous mistakes when they were collecting data as a result of their discussions during the argumentation session. The students, as a result, will want a chance to re-collect data, and the re-collection of data should be encouraged when time allows. This also offers an opportunity to discuss what scientists do when they realize a mistake is made inside the lab.

Topic Connections

Table 18.2 (p. 396) highlights how the investigation can be used to address specific performance expectations from the *NGSS;* learning objectives from AP Physics 1; learning objectives from AP Physics C: Mechanics, *Common Core State Standards,* in English language arts (*CCSS ELA*); and *Common Core State Standards,* Mathematics (*CCSS Mathematics*).

TABLE 18.2

Lab 18 alignment with standards

***NGSS* performance expectation**	• HS-PS2-2: Use mathematical representations to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system.
AP Physics 1 learning objectives	• 1.A.5.1: The student is able to model verbally or visually the properties of a system based on its substructure and to relate this to changes in the system properties over time as external variables are changed. • 3.A.1.2: The student is able to design an experimental investigation of the motion of an object. • 3.A.1.3: The student is able to analyze experimental data describing the motion of an object and is able to express the results of the analysis using narrative, mathematical, and graphical representations. • 4.B.1.1: The student is able to calculate the change in linear momentum of a two-object system with constant mass in linear motion from a representation of the system (data, graphs, etc.). • 4.B.1.2: The student is able to analyze data to find the change in linear momentum for a constant-mass system using the product of the mass and the change in velocity of the center of mass. • 5.A.2.1: The student is able to define open and closed/isolated systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. • 5.D.1.4: The student is able to design an experimental test of an application of the principle of the conservation of linear momentum, predict an outcome of the experiment using the principle, analyze data generated by that experiment whose uncertainties are expressed numerically, and evaluate the match between the prediction and the outcome. • 5.D.2.2: The student is able to plan data collection strategies to test the law of conservation of momentum in a two-object collision that is elastic or inelastic and analyze the resulting data graphically. • 5.D.2.4: The student is able to analyze data that verify conservation of momentum in collisions with and without an external friction force.
AP Physics C: Mechanics learning objectives	• I.D.2.a: Relate mass, velocity, and linear momentum for a moving object, and calculate the total linear momentum of a system of objects. • I.D.3.a(2): Identify situations in which linear momentum, or a component of the linear momentum vector, is conserved. • I.D.3.a(3): Apply linear momentum conservation to one-dimensional elastic and inelastic collisions and two-dimensional completely inelastic collisions.

Literacy connections (*CCSS ELA*)	• *Reading:* Key ideas and details, craft and structure, integration of knowledge and ideas • *Writing:* Text types and purposes, production and distribution of writing, research to build and present knowledge, range of writing • *Speaking and listening:* Comprehension and collaboration, presentation of knowledge and ideas
Mathematics connections (*CCSS Mathematics*)	• *Mathematical practices:* Reason abstractly and quantitatively, construct viable arguments and critique the reasoning of others, use appropriate tools strategically, attend to precision • *Number and quantity:* Reason quantitatively and use units to solve problems, represent and model with vector quantities, perform operations on vectors • *Algebra:* Interpret the structure of expressions, understand solving equations as a process of reasoning and explain the reasoning, solve equations and inequalities in one variable, represent and solve equations and inequalities graphically • *Functions:* Understand the concept of a function and use function notation, interpret functions that arise in applications in terms of the context, analyze functions using different representations, interpret expressions for functions in terms of the situation they model • *Statistics and probability:* Summarize, represent, and interpret data on two categorical and quantitative variables; understand and evaluate random processes underlying statistical experiments; make inferences and justify conclusions from sample surveys, experiments, and observational studies

LAB 18

Lab Handout

Lab 18. Elastic and Inelastic Collisions: Which Properties of a System Are Conserved During a Collision?

Introduction

Physics is the scientific study of time, space, and matter. Some branches of physics, such as cosmology, investigate questions regarding the entire universe (e.g., how old is it, how did it begin). Most branches of physics, however, investigate questions related to smaller scales and systems. When studying a system, a physicist will identify the system and then ask questions about (1) the matter contained in that system, (2) the interactions between matter contained in the system, and (3) how the matter moves in the system. When doing this, the physicist ignores any influences from outside the system during the investigation, while recognizing that those influences are still there. For example, when studying acceleration of an object in free fall due to gravity, a physicist might ignore the influence of air resistance when its effects are less than the uncertainty in the measurements. Systems come in all sizes. Astronomers study systems as large as galaxies. Chemists study systems that can be as small as a few atoms.

Scientists have identified several laws of conservation that are the same across all systems. A conservation law states that some property of an isolated system is the same before and after some specific interaction takes place within that system. The properties of each object in the system, however, do not need to be the same before and after the interaction in order for some property of the system to stay the same. For example, the law of conservation of energy indicates that the total amount of energy in a system stays the same before and after any interaction that takes place between one or more components of that system. To illustrate what the conservation of energy means, consider what happens when a person places a hot metal spoon into a cold cup of water. When the hot metal spoon is placed into the cup, some heat energy will transfer from the spoon into the water, but the total amount of energy of the system remains constant because the energy that transferred from the spoon into the water is still a part of the system. The transfer of energy caused the temperature of the water to increase and the temperature of the metal to decrease but the total amount of energy in the system did not change, so energy is conserved within the system.

When studying the interactions between two or more objects in a system, physicists often try to identify which properties are conserved during the interaction. In the example of putting a hot metal spoon into cold water, energy is conserved but temperature is not. Another type of interaction that physicists often study is a collision. Collisions are a common experience, from billiard balls colliding on a pool table to an asteroid hitting a planet, or, as shown in Figure L18.1, a collision between two cars.

There are a number of properties that could be conserved during a collision. Some examples include acceleration, velocity, force, energy, and momentum. There are likely other properties that might also be conserved during a collision. In this investigation, you will have an opportunity to determine which properties of a system are conserved during a two-car collision.

FIGURE L18.1

A collision between two vehicles

Your Task

Use what you know about momentum, velocity, acceleration, the conservation of energy and matter, and systems and system models to design and carry out an investigation that will allow you to understand what happens to the different properties of a two-car system before and after a collision.

The guiding question of this investigation is, ***Which properties of a system are conserved during a collision?***

Materials

You may use any of the following materials during your investigation:

- Safety glasses or goggles (required)
- Dynamics carts
- Dynamics track
- Bumper kit for the carts
- Video camera
- Computer or tablet with video analysis software
- Electronic or triple beam balance
- Mass set
- Stopwatches
- Ruler

Safety Precautions

Follow all normal lab safety rules. In addition, take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Wash hands with soap and water after completing the lab.

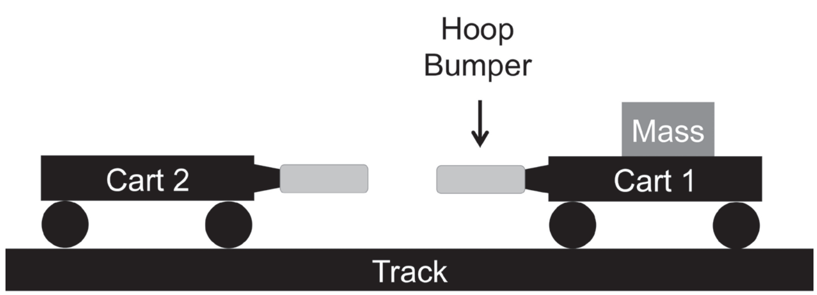
Investigation Proposal Required? ☐ Yes ☐ No

Getting Started

To answer the guiding question you will need to design and carry out two experiments. Figure L18.2 shows how you can set up two carts on a track to examine changes in the velocity, acceleration, and position of each cart before and after a collision. You can also change the nature of the collision by changing the bumpers on the carts. You can use a hoop bumper to make the carts bounce apart after they collide or a Velcro or magnet bumper to make them stick together. To measure changes in velocity, acceleration, and the position of the two carts at the same time, you will need to use a video camera and video analysis software. Before you can design your two experiments, however, you must first determine what type of data you need to collect, how you will collect it, and how you will analyze it.

FIGURE L18.2

One way to measure the velocity, acceleration, or position of a moving object before and after a collision



To determine *what type of data you need to collect,* think about the following questions:

- What are the boundaries and components of the system under study?
- How do the components of the system interact?
- What properties of the system might be conserved?
- What properties of the system are directly measurable?
- What properties of the system will you need to calculate from other measurements?
- What types of collisions will you need to model?
- How can you track how matter and energy flows into, out of, or within this system?
- What will be the independent variable and the dependent variable for each experiment?

To determine *how you will collect the data,* think about the following questions:

- What other factors will you need to control during each experiment?
- Which quantities are vectors, and which quantities are scalars?
- What scale or scales should you use when you take your measurements?
- What equipment will you need to collect the data you need?
- How will you make sure that your data are of high quality (i.e., how will you reduce error)?
- How will you keep track of and organize the data you collect?

To determine *how you will analyze the data,* think about the following questions:

- How will you determine if a property has been conserved during a collision?
- What type of calculations will you need to make?
- What types of comparison will be useful for you to make?
- How could you use mathematics to describe a relationship between variables?
- What type of table or graph could you create to help make sense of your data?

Connections to the Nature of Scientific Knowledge and Scientific Inquiry

As you work through your investigation, you may want to consider

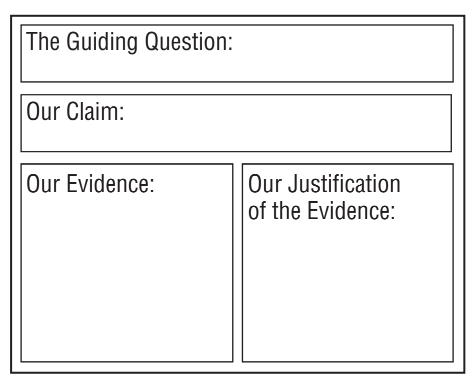
- the difference between laws and theories in science, and
- the difference between data and evidence in science.

Initial Argument

Once your group has finished collecting and analyzing your data, your group will need to develop an initial argument. Your initial argument needs to include a claim, evidence to support your claim, and a justification of the evidence. The *claim* is your group's answer to the guiding question. The *evidence* is an analysis and interpretation of your data. Finally, the *justification* of the evidence is why your group thinks the evidence matters. The justification of the evidence is important because scientists can use different kinds of evidence to support their claims. Your group will create your initial argument on a whiteboard. Your whiteboard should include all the information shown in Figure L18.3.

FIGURE L18.3

Argument presentation on a whiteboard



Argumentation Session

The argumentation session allows all of the groups to share their arguments. One or two members of each group will stay at the lab station to share that group's argument, while the other members of the group go to the other lab stations to listen to and critique the other arguments. This is similar to what scientists do when they propose, support, evaluate, and refine new ideas during a poster session at a conference. If you are presenting your group's argument, your goal is to share your ideas and answer questions. You should also keep a record of the critiques and suggestions made by your classmates so you can use this feedback to make your initial argument stronger. You can keep track of specific critiques and suggestions for improvement that your classmates mention in the space below.

Critiques about our initial argument and suggestions for improvement:

If you are critiquing your classmates' arguments, your goal is to look for mistakes in their arguments and offer suggestions for improvement so these mistakes can be fixed. You should look for ways you to make your initial argument stronger by looking for things that the other groups did well. You can keep track of interesting ideas that you see and hear during the argumentation in the space below. You can also use this space to keep track of any questions that you will need to discuss with your team.

Interesting ideas from other groups or questions to take back to my group:

Once the argumentation session is complete, you will have a chance to meet with your group and revise your initial argument. Your group might need to gather more data or design a way to test one or more alternative claims as part of this process. Remember, your goal at this stage of the investigation is to develop the best argument possible.

Report

Once you have completed your research, you will need to prepare an *investigation report* that consists of three sections. Each section should provide an answer to the following questions:

1. What question were you trying to answer and why?
2. What did you do to answer your question and why?
3. What is your argument?

Your report should answer these questions in two pages or less. This report must be typed, and any diagrams, figures, or tables should be embedded into the document. Be sure to write in a persuasive style; you are trying to convince others that your claim is acceptable or valid!

Checkout Questions

Lab 18. Elastic and Inelastic Collisions: Which Properties Are Conserved During a Collision?

1. In your investigation, the kinetic energy of the system before the collision was greater than the kinetic energy of the system after the collision. Did your investigation violate the law of conservation of energy?

   a. Yes, it violated the law of conservation of energy.
   b. No, it did not violate the law of conservation of energy.

   Explain why or why not.

Use the following information to answer questions 2 and 3. A truck has a mass of 5,000 kg and is moving to the right at 10 m/s. A small car has a mass of 2,000 kg and is moving to the left at 20 m/s. The two vehicles collide head on.

2. Is this collision elastic or inelastic?

   a. Elastic
   b. Inelastic

   How do you know?

3. What is the total momentum of the two-vehicle system before the collision?

   a. 10,000 kg·m/s
   b. 40,000 kg·m/s
   c. 50,000 kg·m/s
   d. 90,000 kg·m/s

   How do you know?

4. The terms *data* and *evidence* mean the same thing in science.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about collisions.

5. It is important to track how energy and matter move into, out of, and within a system and to determine if any of properties are conserved within the system.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about collisions.

6. In science, there is a difference between a law and a theory. What is the difference between a law and a theory? Explain why this distinction is important, using an example from your investigation about collisions.

7. Scientists often need to identify the system under study before they start collecting data. Explain why defining the system under study is so important in science, using an example from your investigation about collisions.

Teacher Notes

Lab 19. Impulse and Materials: Which Material Is Most Likely to Provide the Best Protection for a Phone That Has Been Dropped?

Purpose

The purpose of this lab is for students to *apply* what they know about the core idea of forces and motion, part of the disciplinary core idea (DCI) of Motion and Stability: Forces and Interactions from the *NGSS,* to identify a suitable material for a new protective cell phone case. This lab also gives students an opportunity to learn about the crosscutting concepts (CCs) of (a) Scale, Proportion, and Quantity; and (b) Structure and Function from the *NGSS.* In addition, this lab can be used to help students understand three big ideas from AP Physics: (a) the interactions of an object with other objects can be described by forces, (b) interactions between systems can result in changes in those systems, and (c) changes that occur as result of interactions are constrained by conservation laws. As part of the explicit and reflective discussion, students will also learn about (a) how the culture of science, societal needs, and current events influence the work of scientists; and (b) the nature and role of experiments in science.

Underlying Physics Concepts

Newton's second law is typically written to describe the relationship between the forces acting on an object and the acceleration of that object. This formulation of Newton's second law is shown in Equation 19.1, where $\sum \mathbf{F}$ is the net force acting on an object, m is the mass of that object, and $\mathbf{a}$ is the acceleration of the object. In SI units, force is measured in newtons (N), mass is measured in kilograms (kg), and acceleration is measured in meters per second squared (m/s^2).

$$\textbf{(Equation 19.1)} \quad \sum \mathbf{F} = m\mathbf{a}$$

It turns out, however, that this formulation of the second law does not appear in Newton's major work, *Philosophiae Naturalis Principia Mathematica* (published in 1687). Instead, Newton's second law states that a net force on an object will result in a change in momentum of that object. This is shown mathematically in Equation 19.2, where $\sum \mathbf{F}$ is the net force, Δ (pronounced "delta") means a change in the subsequent quantity, $\mathbf{p}$ is the momentum of the object, and t is the time in which the force acts on the object. In SI units, momentum is measured in kilogram-meters per second (kg·m/s) and time is measured in seconds (s).

$$\text{(Equation 19.2)} \quad \sum \mathbf{F} = \Delta \mathbf{p}/\Delta t$$

Momentum is equal to the mass of an object times the velocity of the object. If we assume that the mass of an object does not change when a net force acts on it (a valid assumption at non-relativistic velocities), then Equation 19.2 can be rewritten as Equation 19.3, where **v** is velocity. In SI units, velocity is measured in meters per second (m/s).

$$\text{(Equation 19.3)} \quad \sum \mathbf{F} = m\Delta \mathbf{v}/\Delta t$$

The quantity $\Delta \mathbf{v}/\Delta t$ is equal to the acceleration of an object. This is why Newton's second law is often written as Equation 19.1, as opposed to Equation 19.2 or 19.3. Because the mass remains constant, an applied force on an object must cause an acceleration. If we multiply both sides of Equation 19.2 by Δt, then we get Equation 19.4:

$$\text{(Equation 19.4)} \quad \sum \mathbf{F}\Delta t = m\Delta \mathbf{v}$$

Newton defined the left side of the equation, $\sum \mathbf{F}\Delta t$, as the "impulse," often given the symbol **J,** measured in units of newton seconds (N·s); this mathematical relationship is shown in Equation 19.5.

$$\text{(Equation 19.5)} \quad \sum \mathbf{F}\Delta t = \mathbf{J}$$

Finally, assuming that the mass of an object remains constant, then Newton's second law implies that an impulse acting on an object will cause a change in the object's velocity. This is shown in Equation 19.6.

$$\text{(Equation 19.6)} \quad \mathbf{J} = m\Delta \mathbf{v}$$

Students will roll a cart with a force probe down a ramp and crash the cart into various materials during this investigation. If the cart's velocity is the same each time the cart collides with a specific material, then the total impulse required to bring the car to rest will remain the same. In other words, the mass of the cart and the velocity of the cart will be the same for each collision. Impulse is a function of both the force acting on an object and the time the force acts on that object. These two variables are inversely related, so that the larger the force, the shorter the amount of time the force acts on the object for a given impulse.

We can represent this graphically. Figure 19.1 (p. 410) shows a force versus time graph for a collision. In this collision, a constant force of 4 N acts on the object and brings it to rest in 2 seconds. Because impulse is equal to force times time, the total impulse acting on the object is 8 N·s. This also happens to be the area underneath the curve for a force versus time graph.

FIGURE 19.1

A force versus time graph, with a constant force of 4 N acting on the object

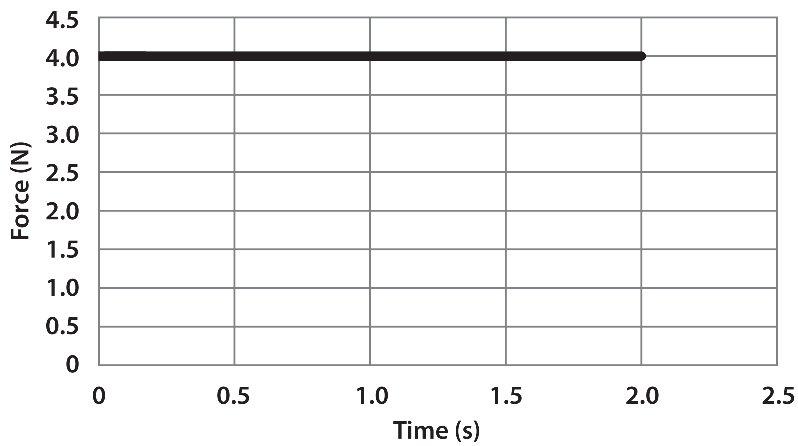
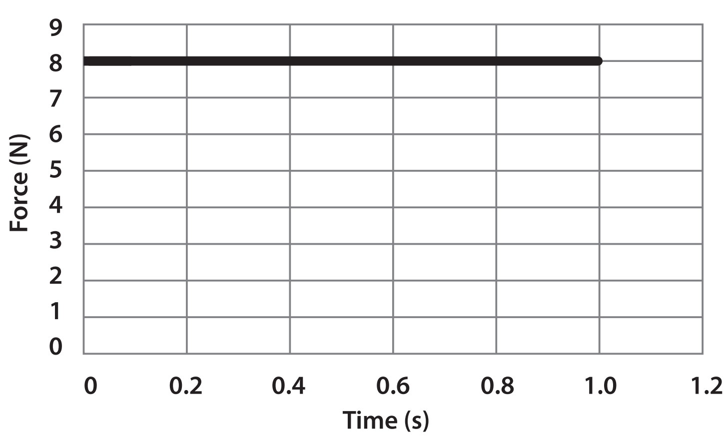


Figure 19.2 shows another force versus time graph. In this case, the force acting on the object is 8 N. However, this force only needs to act on the object for 1 second to bring the object to rest. In this case, the impulse is also 8 N·s.

FIGURE 19.2

A force versus time graph, with a constant force of 8 N acting on the object



Students will be able to create force versus time graphs for each collision. If the velocity and mass of the cart before impact is constant for all materials tested, then the total impulse required to bring the cart to rest will be the same for all materials. However, the force versus time graph will be different for each material. The "best" material for a cell phone case is the one that results in the force being minimized and the time the collision takes place being maximized. It is the magnitude of the force that will damage the cell phone, so the best material is the one that minimizes the force acting on the cart during the collision.

Finally, the graphs students create will not appear linear like those shown in Figures 19.1 and 19.2. Instead, they will be curved. For students who are in calculus, this provides an opportunity to show contextual applications of integration. The integral of the force versus time graph will give the impulse. For those students who are not in calculus, they can still "qualitatively" answer the guiding question by making comparisons between graphs.

Timeline

The instructional time needed to complete this lab investigation is 200–280 minutes. Appendix 3 (p. 531) provides options for implementing this lab investigation over several class periods. Option C (230 minutes) should be used if students are unfamiliar with scientific writing, because this option provides extra instructional time for scaffolding the writing process. You can scaffold the writing process by modeling, providing examples, and providing hints as students write each section of the report. Option E can also be used if students are unfamiliar with any of the data collection and analysis tools. Option F (200 minutes) should be used if students are familiar with scientific writing and have developed the skills needed to write an investigation report on their own. In option F, students complete stage 6 (writing the investigation report) and stage 8 (revising the investigation report) as homework.

Materials and Preparation

The materials needed to implement this investigation are listed in Table 19.1 (p. 412). The items can be purchased from a science supply company such as Carolina, Flinn Scientific, PASCO, Vernier, or Ward's Science. The data collection and analysis software can be purchased from Vernier (Logger *Pro*) or PASCO (SPARKvue or Capstone). These companies also have apps that can be used on Apple- or Android-based tablets and cell phones. We recommend consulting with your school's information technology coordinator to determine the best option for your students.

TABLE 19.1

Materials list for Lab 19

Item	Quantity
Safety glasses or goggles	1 per student
Dynamics cart	1 per group
Dynamics track	1 per group
Force sensor	1 per group
Sensor interface	1 per group
Computer, tablet, or graphing calculator with data collection and analysis software	1 per group
Foam block	1 per group
Plastic block	1 per group
Rubber block	1 per group
Wooden block	1 per group
Metal block	1 per group
Investigation proposal A (optional)	1 per group
Whiteboard, 2' × 3'*	1 per group
Lab Handout	1 per student
Peer-review guide and teacher scoring rubric	1 per student
Checkout Questions	1 per student

* As an alternative, students can use computer and presentation software such as Microsoft PowerPoint or Apple Keynote to create their arguments.

Be sure to use a set routine for distributing and collecting the materials during the lab investigation. One option is to set up the materials for each group at each group's lab station before class begins. This option works well when there is a dedicated section of the classroom for lab work and the materials are large and difficult to move (such as a dynamics track). A second option is to have all the materials on a table or cart at a central location. You can then assign a member of each group to be the "materials manager." This individual is responsible for collecting all the materials his or her group needs from the table or cart during class and for returning all the materials at the end of the class. This option works well when the materials are small and easy to move (such as stopwatches, metersticks, or hanging masses). It also makes it easy to inventory the materials at the end of the class before students leave for the day.

Safety Precautions

Remind students to follow all normal lab safety rules. In addition, tell students to take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Wash hands with soap and water after completing the lab.

Topics for the Explicit and Reflective Discussion

Reflecting on the Use of Core Ideas and Crosscutting Concepts During the Investigation

Teachers should begin the explicit and reflective discussion by asking students to discuss what they know about the core idea they used during the investigation. The following are some important concepts related to the core idea of forces and motion that students will need to identify a suitable material for a new protective cell phone case:

- The change in momentum of an object is a vector quantity in the direction of the net force exerted on the object.
- The change in momentum of an object occurs over a time interval.
- The force that one object exerts on a second object changes the momentum of the second object (in the absence of other forces on the second object).
- An *impulse* is the product of the average force acting on an object and the time interval during which the interaction occurred.

To help students reflect on what they know about forces and motion, we recommend showing them two or three images using presentation software that help illustrate these important ideas. You can then ask the students the following questions to encourage them to share how they are thinking about these important concepts:

1. What do we see going on in this image?
2. Does anyone have anything else to add?
3. What might be going on that we can't see?
4. What are some things that we are not sure about here?

You can then encourage students to think about how CCs played a role in their investigation. There are at least two CCs that students need to identify a suitable material for a new protective cell phone case: (a) Scale, Proportion, and Quantity; and (b) Structure and Function (see Appendix 2 [p. 527] for a brief description of these CCs). To help students reflect on what they know about these CCs, we recommend asking them the following questions:

1. Why is it important to think about issues of scale and quantity during an investigation?
2. What scales and quantities did you use during your investigation? Why was it useful?
3. The way an object is shaped or structured determines many of its properties and how it functions. Why is it useful to think about the relationship between structure and function during an investigation?
4. Why was it useful to examine the structure of a material when attempting to determine its ability to function as a protective cell phone case?

You can then encourage the students to think about how they used all these different concepts to help answer the guiding question and why it is important to use these ideas to help justify their evidence for their final arguments. Be sure to remind your students to explain why they included the evidence in their arguments and make the assumptions underlying their analysis and interpretation of the data explicit in order to provide an adequate justification of their evidence.

Reflecting on Ways to Design Better Investigations

It is important for students to reflect on the strengths and weaknesses of the investigation they designed during the explicit and reflective discussion. Students should therefore be encouraged to discuss ways to eliminate potential flaws, measurement errors, or sources of uncertainty in their investigations. To help students be more reflective about the design of their investigation and what they can do to make their investigations more rigorous in the future, you can ask them the following questions:

1. What were some of the strengths of the way you planned and carried out your investigation? In other words, what made it scientific?
2. What were some of the weaknesses of the way you planned and carried out your investigation? In other words, what made it less scientific?
3. What rules can we make, as a class, to ensure that our next investigation is more scientific?

Reflecting on the Nature of Scientific Knowledge and Scientific Inquiry

This investigation can be used to illustrate two important concepts related to the nature of scientific knowledge and the nature of scientific inquiry: (a) how the culture of science, societal needs, and current events influence the work of scientists; and (b) the nature and role of experiments in science (see Appendix 2 for a brief description of these two concepts). Be sure to review these concepts during and at the end of the explicit and reflective discussion. To help students think about these concepts in relation to what they did during the lab, you can ask them the following questions:

1. People view some types of research as being more important than other types of research because of cultural values and current events. Can you come up with some examples of how cultural values and current events have influenced the work of scientists?
2. Scientists share a set of values, norms, and commitments that shape what counts as knowing, how to represent or communicate information, and how to interact with other scientists. Can you work with your group to come up with a rule that you can use to decide if something is science or not science? Be ready to share in a few minutes.
3. I asked you to design and carry out an experiment as part of your investigation. Can you give me some examples of what experiments are used for in science?
4. Can you work with your group to come up with a rule that you can use to decide if an investigation is an experiment or not? Be ready to share in a few minutes.

You can also use presentation software or other techniques to encourage your students to think about these concepts. You can show examples of research projects that were influenced by cultural values and current events and ask students to think about what was going on at the time and why that research was viewed as being important for the greater good. You can also show images of different types of investigations (such as a physicist or an astronomer collecting data using a telescope as part of an observational or descriptive study, a person working in the library doing a literature review, a person working on a computer to analyze an existing data set, and an actual experiment) and ask students to indicate if they think each image represents an experiment and why or why not.

Be sure to remind your students that, to be proficient in science, it is important that they understand what counts as scientific knowledge and how that knowledge develops over time.

Hints for Implementing the Lab

- Allowing students to design their own procedures for collecting data gives students an opportunity to try, to fail, and to learn from their mistakes. However, you can scaffold students as they develop their procedure by having them fill out an investigation proposal. These proposals provide a way for you to offer students hints and suggestions without telling them how to do it. You can also check the proposals quickly during a class period. For this lab we suggest using Investigation Proposal A.

- Be sure to use blocks that are the same size.
- Encourage students to measure or calculate several different physical properties of the blocks. This information will enable them to relate the structure (physical properties) of the blocks to their function (decrease the force and increase the time of the collision).
- Learn how to use the dynamics cart and track, the force sensor, and the data collection and analysis software before the lab begins. It is important for you to know how to use the equipment so you can help students when technical issues arise.
- Allow students to become familiar with the dynamics cart and track, the force sensor, and the data collection and analysis software as part of the tool talk before they begin to design their investigation. Giving them 5–10 minutes to examine the available equipment and materials will let them see what they can and cannot do with them. This also gives students a chance to begin thinking about what variables to test and how to control for other variables.
- This lab provides students with an important opportunity to think about controlling variables in scientific investigations. Specifically, students must control the velocity and mass of the cart before impact. Students may also want to control the shape, mass, or size of the materials used during the collision. However, if students do not control these variables, this provides an important learning opportunity for the explicit and reflective discussion.
- Be sure to allow students to go back and re-collect data at the end of the argumentation session. Students often realize that they made numerous mistakes when they were collecting data as a result of their discussions during the argumentation session. The students, as a result, will want a chance to re-collect data, and the re-collection of data should be encouraged when time allows. This also offers an opportunity to discuss what scientists do when they realize a mistake is made inside the lab.

Connections to Standards

Table 19.2 highlights how the investigation can be used to address specific performance expectations from the *NGSS;* learning objectives from AP Physics 1; learning objectives from AP Physics C: Mechanics, *Common Core State Standards,* in English language arts (*CCSS ELA*); and *Common Core State Standards,* Mathematics (*CCSS Mathematics*).

TABLE 19.2

Lab 19 alignment with standards

***NGSS* performance expectations**	• HS-PS2-2: Use mathematical representations to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system. • HS-PS2-3: Apply scientific and engineering ideas to design, evaluate, and refine a device that minimizes the force on a macroscopic object during a collision.
AP Physics 1 learning objectives	• 3.D.1.1: The student is able to justify the selection of data needed to determine the relationship between the direction of the force acting on an object and the change in momentum caused by that force. • 3.D.2.1: The student is able to justify the selection of routines for the calculation of the relationships between changes in momentum of an object, average force, impulse, and time of interaction. • 3.D.2.2: The student is able to predict the change in momentum of an object from the average force exerted on the object and the interval of time during which the force is exerted. • 3.D.2.3: The student is able to analyze data to characterize the change in momentum of an object from the average force exerted on the object and the interval of time during which the force is exerted. • 3.D.2.4: The student is able to design a plan for collecting data to investigate the relationship between changes in momentum and the average force exerted on an object over time.
AP Physics C: Mechanics learning objectives	• I.B.2.b: Students should understand how Newton's second law applies to an object subject to forces such as gravity, the pull of strings, or contact forces. • I.D.2.a: Relate mass, velocity, and linear momentum for a moving object, and calculate the total linear momentum of a system of objects. • I.D.2.b: Relate impulse to the change in linear momentum and the average force acting on an object. • I.D.2.c: State and apply the relations between linear momentum and center-of-mass motion for a system of particles. • I.D.2.d: Calculate the area under a force versus time graph and relate it to the change in momentum of an object. • I.D.2.e: Calculate the change in momentum of an object given a function $\mathbf{F}(t)$ for the net force acting on the object.
Literacy connections (*CCSS ELA*)	• *Reading:* Key ideas and details, craft and structure, integration of knowledge and ideas • *Writing:* Text types and purposes, production and distribution of writing, research to build and present knowledge, range of writing • *Speaking and listening:* Comprehension and collaboration, presentation of knowledge and ideas

continued

Table 19.2 (*continued*)

Mathematics connections (*CCSS Mathematics*)	• *Mathematical practices:* Reason abstractly and quantitatively, construct viable arguments and critique the reasoning of others, use appropriate tools strategically, attend to precision • *Number and quantity:* Reason quantitatively and use units to solve problems, represent and model with vector quantities, perform operations on vectors • *Algebra:* Interpret the structure of expressions, understand solving equations as a process of reasoning and explain the reasoning, solve equations and inequalities in one variable, represent and solve equations and inequalities graphically • *Functions:* Understand the concept of a function and use function notation, interpret functions that arise in applications in terms of the context, analyze functions using different representations, interpret expressions for functions in terms of the situation they model • *Statistics and probability:* Summarize, represent, and interpret data on two categorical and quantitative variables; understand and evaluate random processes underlying statistical experiments; make inferences and justify conclusions from sample surveys, experiments, and observational studies

Reference

Newton, I. 1687. *Philosophiae naturalis principia mathematica* [Mathematical principles of natural philosophy]. London: S. Pepys.

Lab Handout

Lab 19. Impulse and Materials: Which Material Is Most Likely to Provide the Best Protection for a Phone That Has Been Dropped?

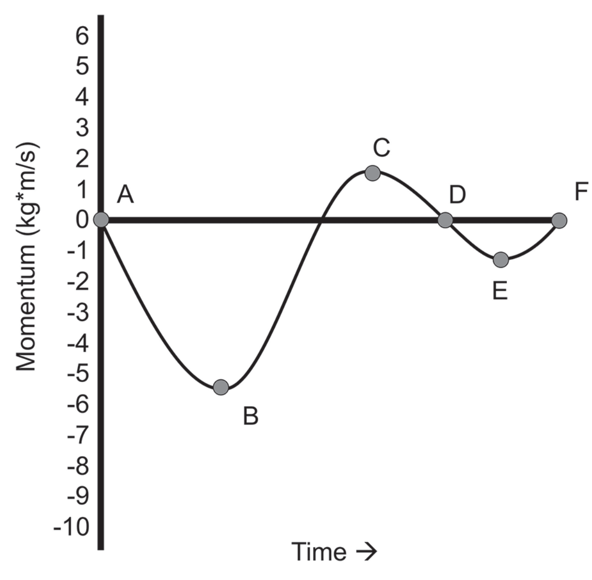
Introduction

People throughout the United States use personal electronic devices. On any given day, a person might use a cell phone, smartwatch, laptop computer, or tablet in a number of different settings. Unfortunately, people often damage these devices by accidently dropping them or knocking them off a table. Most consumers, however, do not want to replace any of these devices on a regular basis because they tend to be expensive. This is one reason why so many people use a case to protect their different personal electronic devices. Many different companies sell cases that are designed to prevent phones, tablets, or laptops from breaking when they are dropped or knocked off a table.

When a person drops a cell phone, the force of gravity causes the phone to accelerate toward the ground at -9.8 m/s^2. Any object with a velocity has momentum, and as an object accelerates during free fall, its momentum increases. Upon reaching the ground, the ground exerts an upward, normal force that causes the momentum of the object to change. Figure L19.1 is an example of a momentum versus time graph for a cell phone that falls toward and then strikes the ground, bouncing upward once, and then coming to rest. Point A in the graph corresponds to the cell phone falling out of a person's hand. Between points B and C, the cell phone is hitting the ground, with the ground exerting a force on the cell phone, causing it to bounce back up. In other words, the segment of the graph between points B and C corresponds to the collision between the phone and the ground. At point D, the cell phone has reached the highest point of its bounce, and then at point E, the cell phone hits the ground and finally comes to rest at point F. The segment of the graph between E and F corresponds to the second collision between the phone and the ground.

FIGURE L19.1

Momentum versus time graph for a falling cell phone



Cell phones tend to break easily when dropped because they are made out of lightweight materials, such as glass, aluminum, and plastic, which have a relatively low breaking point. The breaking point of a material is the maximum amount of force that it can absorb before it deforms. Companies make cell phones out of these materials because it allows the companies to make phones that are thin and light so they are easy to carry around. Unfortunately, a phone that is thin and light is also fragile.

Protective cases help alleviate this design trade-off. Protective phone cases tend to be made from a material that has two important characteristics. First, the material must be able to minimize the force that acts on the phone during a collision. This is important because the change of momentum associated with a phone in free fall suddenly hitting the ground is a vector that acts in the direction of the net force exerted on it. Second, the material must be able to maximize the time of the collision. This characteristic is important to consider because any change in momentum happens over a specific time interval. Your goal in this investigation is to use this information to identify a suitable material for a new protective cell phone case.

Your Task

Use what you know about momentum, impulses, the relationship between structure and function, and scale, proportional relationships, and vector quantities to design and carry out an investigation to compare how different materials change the momentum of an object during a collision.

The guiding question for this investigation is, ***Which material is most likely to provide the best protection for a phone that has been dropped?***

Materials

You may use any of the following materials during your investigation:

- Safety glasses or goggles (required)
- Dynamics cart
- Dynamics track
- Force sensor
- Sensor interface
- Computer, tablet, or graphing calculator with data collection and analysis software
- Foam block
- Plastic block
- Rubber block
- Wooden block
- Metal block

Safety Precautions

Follow all normal lab safety rules. In addition, take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.

3. Wash hands with soap and water after completing the lab.

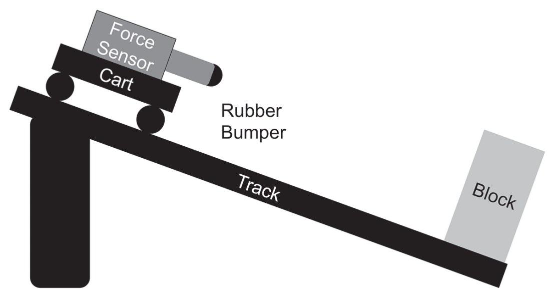
Investigation Proposal Required? ☐ Yes ☐ No

Getting Started

To answer the guiding question, you will need to investigate how different materials change the momentum of an object during a collision. Figure L19.2 shows how you can attach a force sensor to a cart and then roll it down a frictionless track on an incline. The end of the force sensor should collide with the material you are testing at the end of the track. Starting the cart at the same point on the track for each test will allow you to control for the momentum of the cart prior to the collision with the block. Before you can begin to design your investigation using this equipment, however, you must determine what type of data you need to collect, how you will collect it, and how you will analyze it.

FIGURE L19.2

One way to examine the change in momentum of the cart after a collision with a specific material



To determine *what type of data you need to collect,* think about the following questions:

- How might changes in the structure of a cell phone case affect the function of the case?
- What are the components of this system and how do they interact?
- How can you describe the components of the system quantitatively?
- How do you quantify a change in momentum?
- What measurements do you need to make?
- What will be the independent variable and the dependent variable for your experiment?

To determine *how you will collect the data*, think about the following questions:

- What other variables do you need to measure or control?
- What scale or scales should you use when you take your measurements?
- Which quantities are vectors, and which quantities are scalars?
- For any vector quantities, which directions are positive and which directions are negative?

- How will you make sure that your data are of high quality (i.e., how will you reduce error)?
- How will you keep track of and organize the data you collect?

To determine *how you will analyze the data,* think about the following questions:

- What type of calculations will you need to make?
- What types of comparisons will be useful?
- How could you use mathematics to document a difference between materials?
- What type of table or graph could you create to help make sense of your data?

Connections to the Nature of Scientific Knowledge and Scientific Inquiry

As you work through your investigation, you may want to consider

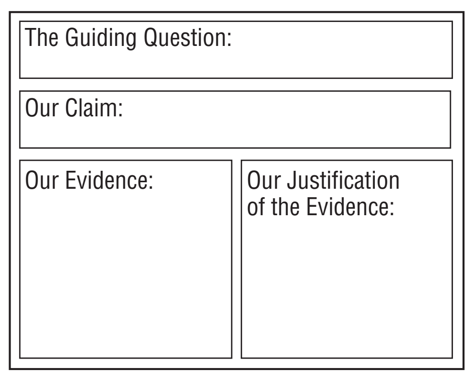
- how the culture of science, societal needs, and current events influence the work of scientists; and
- the nature and role of experiments in science.

Initial Argument

Once your group has finished collecting and analyzing your data, your group will need to develop an initial argument. Your initial argument needs to include a claim, evidence to support your claim, and a justification of the evidence. The *claim* is your group's answer to the guiding question. The *evidence* is an analysis and interpretation of your data. Finally, the *justification* of the evidence is why your group thinks the evidence matters. The justification of the evidence is important because scientists can use different kinds of evidence to support their claims. Your group will create your initial argument on a whiteboard. Your whiteboard should include all the information shown in Figure L19.3.

FIGURE L19.3

Argument presentation on a whiteboard



Argumentation Session

The argumentation session allows all of the groups to share their arguments. One or two members of each group will stay at the lab station to share that group's argument, while the other members of the group go to the other lab stations to listen to and critique the other arguments. This is similar to what scientists do when they propose, support, evaluate, and refine new ideas during a poster session at a conference. If you are presenting your group's argument, your goal is to share your ideas and answer questions. You should also keep a record of the critiques and suggestions made by your classmates so you can use this feedback to make your initial argument stronger. You can keep track of specific critiques and suggestions for improvement that your classmates mention in the space below.

Critiques about our initial argument and suggestions for improvement:

If you are critiquing your classmates' arguments, your goal is to look for mistakes in their arguments and offer suggestions for improvement so these mistakes can be fixed. You should look for ways to make your initial argument stronger by looking for things that the other groups did well. You can keep track of interesting ideas that you see and hear during the argumentation in the space below. You can also use this space to keep track of any questions that you will need to discuss with your team.

Interesting ideas from other groups or questions to take back to my group:

Once the argumentation session is complete, you will have a chance to meet with your group and revise your initial argument. Your group might need to gather more data or design a way to test one or more alternative claims as part of this process. Remember, your goal at this stage of the investigation is to develop the best argument possible.

Report

Once you have completed your research, you will need to prepare an *investigation report* that consists of three sections. Each section should provide an answer to the following questions:

1. What question were you trying to answer and why?
2. What did you do to answer your question and why?
3. What is your argument?

Your report should answer these questions in two pages or less. This report must be typed, and any diagrams, figures, or tables should be embedded into the document. Be sure to write in a persuasive style; you are trying to convince others that your claim is acceptable or valid!

Checkout Questions

Lab 19. Impulse and Materials: Which Material Is Most Likely to Provide the Best Protection for a Phone That Has Been Dropped?

1. How might your lab results regarding force, impulse, and momentum inform engineers when they design cars? How can this information help keep people safe during a collision between two cars?

2. Scientists and engineers who study ways to transport people to other planets must account for a number of challenges in the design of spaceships. One problem is how to get a large spaceship to move with a fast enough velocity. In response, some have suggested using a solar sail, where a ship uses a specially designed sail to catch microscopic particles continuously emitted by the Sun. How do the results of your lab relate to solar sails? Why might scientists think solar sails are a good solution?

3. How an object is structured is related to its function.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about impulse and momentum.

4. The research done by a scientist is often influenced by current events or what is important in society.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about impulse and momentum.

5. Experiments are one type of research design used by scientists. Explain what an experiment is and what types of questions are best answered using an experiment, using examples from your investigation about impulse and momentum as well as from previous investigations in this class or your previous science classes.

6. Scientists often need to think about scales, proportional relationships, and vector quantities during an investigation. Explain why it is important for scientists to think about these things, using examples from your investigation about impulse and momentum as well as from previous investigations in this class or your previous science classes.

SECTION 7
Energy, Work, and Power

Introduction Labs

Teacher Notes

Lab 20. Kinetic and Potential Energy: How Can We Use the Work-Energy Theorem to Explain and Predict Behavior of a System That Consists of a Ball, a Ramp, and a Cup?

Purpose

The purpose of this lab is to *introduce* students to the disciplinary core idea (DCI) of Energy from the *NGSS* by having them use the work-energy theorem to explain and predict the behavior of a system that consists of a ball, a ramp, and a cup. This lab also gives students an opportunity to learn about the crosscutting concepts (CCs) of (a) Systems and System Models and (b) Energy and Matter: Flows, Cycles, and Conservation from the *NGSS*. In addition, this lab can be used to help students understand three big ideas from AP Physics: (a) objects and systems have properties such as mass and charge, (b) the interactions of an object with other objects can be described by forces, and (c) changes that occur as result of interactions are constrained by conservation laws. As part of the explicit and reflective discussion, students will also learn about (a) how scientific knowledge changes over time and (b) the difference between laws and theories in science.

Underlying Physics Concepts

The work-energy theorem states that work done by a force acting on an object over a displacement results in a change in the energy of the object. The change can be in terms of the type of energy or the amount of energy. In this lab, work is done by gravity to convert the energy of the ball from potential energy at the top of the ramp to kinetic energy at the bottom of the ramp. Work is then done by friction to dissipate the kinetic energy of the ball once it enters the cup as heat, eventually resulting in the ball and cup coming to rest.

To understand the work done by gravity, we first start with the law of conservation of energy. The law of conservation of energy states that in a closed system the total energy of the system is conserved. The energy of an object can be described based on its potential energy and kinetic energy. Potential energy is stored energy of position. Gravitational potential energy is stored energy due to an object's location in a gravitational field. Kinetic energy is the energy an object has due to its motion. The potential energy, PE, and kinetic energy, KE, of a ball on a ramp can be calculated using Equations 20.1 and 20.2, where m is the mass, $\mathbf{g}$ is the acceleration due to gravity, $\mathbf{h}$ is the height, and $\mathbf{v}$ is the velocity. In SI units, energy is measured in joules (J), mass is measured in kilograms (kg), height is measured in meters (m), and velocity is measured in meters per second (m/s). The acceleration due to gravity is constant and equal to 9.8 m/s^2.

(Equation 20.1) $\quad \mathrm{PE} = m\mathbf{gh}$

$$\textbf{(Equation 20.2)} \quad KE = \tfrac{1}{2}m\mathbf{v}^2$$

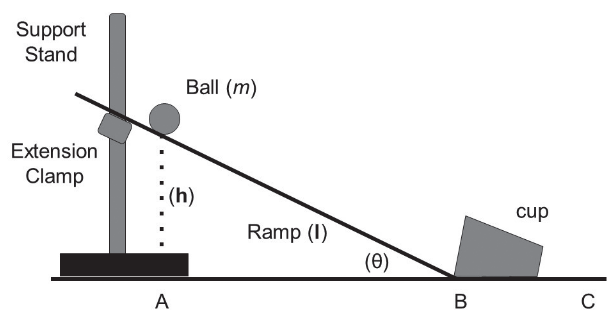
The total mechanical energy of an object is the sum total of its individual types of energy. This means that the total mechanical energy of an object (ME) is the sum of its potential and kinetic energy, shown in Equation 20.3.

$$\textbf{(Equation 20.3)} \quad ME = PE + KE$$

There exist three unique points in the experiment where the kinetic and potential energies of the ball can be calculated, as shown in Figure 20.1. At point A, $PE_A = m\mathbf{gh}$ because the ball is in a gravitational field of height **h.** At point A, $KE_A = 0$ since the ball is at rest. Thus, at point A, all of the mechanical energy of the ball is in the form of potential energy. At point B, $PE_B = 0$ because the ball has a height of zero meters above the ground in the gravitational field, and $KE_B = \tfrac{1}{2}m\mathbf{v}^2$ because the ball has a non-zero velocity. At point B, all of the energy of the ball is in the form of kinetic energy.

FIGURE 20.1

Energies at points A, B, and C for a ball of mass *m* rolling down a ramp of length l at an angle of inclination θ



Note that because the total energy of a system is conserved, the total energy at point A must be equal to the total energy at point B. However, the type of energy of the ball has changed from point A to point B. Thus, work must have been done on the ball between these two points. As mentioned previously, work is a force acting on an object over a displacement. When the ball moves from point A to point B, the force acting on the ball is gravity. Thus, work is done by gravity to change the energy of the ball from potential energy to kinetic energy.

Furthermore, as we have established, the kinetic energy at point A is equal to zero and the potential energy at point B is equal to zero. Thus, $PE_A = KE_B$ and therefore $m\mathbf{gh} = \tfrac{1}{2}m\mathbf{v}^2$ when the ball moves from point A to B. The mass value on both sides of the equation "divides to 1" (the more mathematically appropriate term for the commonly used "cancels out"), indicating that the mass of the ball does not affect the velocity of the ball at the bottom of the ramp.

The total energy of the ball at any point between point A and point B is constant. That is, the sum total of the potential energy and kinetic energy of the ball will not change as it rolls down the incline. Thus, the height and the velocity of the ball at point A will determine the total energy of the system. In most cases, the ball is released from rest. This means the total energy of the ball is a function of the height of point A above ground level. After the ball and cup have come to rest at point C, $PE_C = 0$ and $KE_C = 0$ since the ball and cup have a height and velocity of zero. In this instance, work done on the ball and cup results in a loss of energy.

The students can calculate the displacement of the ball and the cup before they come to rest after the collision at point B to verify KE_B. That is, the farther the cup moves (or the longer it takes for the cup to come to rest), the more energy the ball must have had at the bottom of the ramp. This is because the frictional force between the cup and the ground results in work being done on the cup to bring it to rest. The work-energy theorem states that work done on an object changes the mechanical energy of the object. This means work can be done to increase the mechanical energy, or, in the case of work done by friction, work can be done to decrease the mechanical energy of an object.

We can express this mathematically using the following approach. Work done by friction is directly proportional to the distance that it takes an object to come to rest—the longer the distance, the more work is done to bring the object to rest (assuming a constant force). Thus, the longer the distance it takes the cup to come to rest, the more work was done to dissipate the kinetic energy of the cup, and the more kinetic energy the cup must have had. Equation 20.4 shows the relationship between work and force, where W is work, $\mathbf{F}$ is force, and $\mathbf{x}$ is displacement. In SI units, work is measured in joules (J), force is measured in newtons (N), and displacement is measured in meters (m).

$$\textbf{(Equation 20.4)} \quad W = \mathbf{Fx}$$

Notice that work is measured in joules; this makes sense, because work leads to a change in the mechanical energy of an object, and energy is also measured in joules. Recognizing this fact, we can also relate the work done by friction to bring the cup to a stop to the kinetic energy of the ball at the bottom of the ramp by setting these two quantities equal to each other. This gives us Equation 20.5. In this equation, $\mathbf{F_{fr}}$ is the frictional force acting on the cup. Note that to calculate the force of friction acting on the cup, one must account for the mass of both the cup and the ball inside the cup. However, the value for the mass on the right side of the equation is only the mass of the ball prior to the ball entering the cup, because the cup does not have kinetic energy prior to the ball entering the cup.

$$\textbf{(Equation 20.5)} \quad \mathbf{F_{fr}x} = \tfrac{1}{2}m\mathbf{v}^2$$

Because the kinetic energy at the bottom of the ramp is equal to the potential energy of the ball at the top of the ramp, we can also set the work done by friction to bring the cup to rest equal to the potential energy of the ball at the top of the ramp, shown in Equation 20.6. Again, recognize that the mass on the right side of the equation is only the mass of the ball, whereas to calculate the force of friction on the cup, one must account for both the mass of the ball and the mass of the cup.

$$\textbf{(Equation 20.6)}\quad \mathbf{F_{fr}x} = m\mathbf{gh}$$

To perform these calculations, we need to make several assumptions about the system. First, we must assume there is no friction between the ball and the ramp between points A and B in Figure 20.1. We also must assume that as the ball moves down the ramp (a) all of the potential energy transforms into translational kinetic energy and (b) none of the potential energy is transformed into rotational kinetic energy of the ball. Finally, we must assume that the collision between the ball and the cup at the bottom of the ramp is elastic, which means no kinetic energy is lost when the ball hits the back of the cup and they both begin to move. This approach makes sense, because we have identified the major factors in the motion of the ball. However, the empirical results will not match the predicted results that are derived from Equations 20.1–20.6. Because of this, we strongly recommend that students only build a conceptual model that identifies major relationships.

Timeline

The instructional time needed to complete this lab investigation is 170–230 minutes. Appendix 3 (p. 531) provides options for implementing this lab investigation over several class periods. Option C (230 minutes) should be used if students are unfamiliar with scientific writing, because this option provides extra instructional time for scaffolding the writing process. You can scaffold the writing process by modeling, providing examples, and providing hints as students write each section of the report. Option C can also be used if you are introducing students to the video analysis programs. Option D (170 minutes) should be used if students are familiar with scientific writing and have developed the skills needed to write an investigation report on their own. In option D, students complete stage 6 (writing the investigation report) and stage 8 (revising the investigation report) as homework.

Materials and Preparation

The materials needed to implement this investigation are listed in Table 20.1 (p. 436). The items can be purchased from a science supply company such as Carolina, Flinn Scientific, PASCO, Vernier, or Ward's Science. The 25 mm balls can be purchased as a set (often called a drilled ball set in science supply catalogs). These sets usually include two of each type of ball (brass, aluminum, steel, cork, wood, and copper).

The PVC pipe can be purchased at a home improvement store such as Home Depot or Lowe's. You can make six 1 m long ramps from one 10 ft. long piece of PVC pipe. To make the ramps, first cut the 10 ft. long PVC pipe into three equal-length pieces (each piece will be approximately 1 m in length) and then cut each 1 m piece lengthwise.

The use of video analysis is recommended for this lab. The video analysis software can be purchased from Vernier (Logger *Pro*) or PASCO (SPARKvue or Capstone). These companies also have apps that can be used on Apple- or Android-based tablets and cell phones. We recommend consulting with your school's information technology coordinator to determine the best option for your students.

TABLE 20.1

Materials list for Lab 20

Item	Quantity
Safety glasses or goggles	1 per student
Support stand	1 per group
Extension clamp	1 per group
Set of 25 mm balls (includes brass, aluminum, steel, cork, wood, and copper)	1 per group
PVC pipe (2 in. diameter, 1 m in length)	1 per group
Electronic or triple beam balance	1 per group
Plastic cup	1 per group
Meterstick	2 per group
Protractor	1 per group
Stopwatch	1 per student
Investigation Proposal A (optional)	1 per group
Whiteboard, 2' × 3'*	1 per group
Lab Handout	1 per student
Peer-review guide and teacher scoring rubric	1 per student
Checkout Questions	1 per student
Equipment for video analysis (optional)	
Video camera	1 per group
Computer or tablet with video analysis software	1 per group

* As an alternative, students can use computer and presentation software such as Microsoft PowerPoint or Apple Keynote to create their arguments.

Be sure to use a set routine for distributing and collecting the materials during the lab investigation. One option is to set up the materials for each group at each group's lab station before class begins. This option works well when there is a dedicated section of the classroom for lab work and the materials are large and difficult to move (such as a dynamics track). A second option is to have all the materials on a table or cart at a central location. You can then assign a member of each group to be the "materials manager." This individual is responsible for collecting all the materials his or her group needs from the table or cart during class and for returning all the materials at the end of the class. This option works well when the materials are small and easy to move (such as stopwatches, metersticks, or hanging masses). It also makes it easy to inventory the materials at the end of the class before students leave for the day.

Safety Precautions

Remind students to follow all normal lab safety rules. In addition, tell students to take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Wash hands with soap and water after completing the lab.

Topics for the Explicit and Reflective Discussion

Reflecting on the Use of Core Ideas and Crosscutting Concepts During the Investigation

Teachers should begin the explicit and reflective discussion by asking students to discuss what they know about the core idea they used during the investigation. The following are some important concepts related to the core idea of Energy that students will need to explain the behavior of a system that consist of a ball, a ramp, and a cup using the work-energy theorem:

- Energy is conserved in all systems under all circumstances.
- Conserved quantities are constant in an isolated or a closed system. An *open system* is one that exchanges any conserved quantity with its surroundings.
- The mechanical energy of a system includes the kinetic energy of the objects that make up the system and the potential energy of the configuration of the objects that make up the system.
- Changes in the potential energy of a system can result in changes to the kinetic energy of the system because energy is constant in a closed system.
- *Work* is defined as the product of a force applied on an object or system of objects over a displacement. Work done on an object or a system of objects results in

a change in the type of energy (e.g., work done by gravity to change potential energy to kinetic energy) or a change in the amount of energy (e.g., work done by friction dissipates kinetic energy, thus bringing a moving object to rest).

To help students reflect on what they know about energy, we recommend showing them two or three images using presentation software that help illustrate these important ideas. You can then ask the students the following questions to encourage them to share how they are thinking about these important concepts:

1. What do we see going on in this image?
2. Does anyone have anything else to add?
3. What might be going on that we can't see?
4. What are some things that we are not sure about here?

You can then encourage students to think about how crosscutting concepts (CCs) played a role in their investigation. There are at least two CCs that students need to explain the behavior of a system that consist of a ball, a ramp, and a cup using the work-energy theorem: (a) Systems and System Models and (b) Energy and Matter: Flows, Cycles, and Conservation (see Appendix 2 [p. 527] for a brief description of these CCs). To help students reflect on what they know about these CCs, we recommend asking them the following questions:

1. Scientists often need to define the system under study and then make a model during an investigation. Why is developing a model of system so useful in science?
2. What were the boundaries and components of the system you studied during this investigation? What were the strengths and limitations of the model you developed?
3. Scientists often attempt to track how energy and matter move into, out of, and within systems as part of an investigation. Why is this useful?
4. How did you attempt to track how energy moves within the system you were studying? What did tracking energy allow you to do during your investigation?

You can then encourage the students to think about how they used all these different concepts to help answer the guiding question and why it is important to use these ideas to help justify their evidence for their final arguments. Be sure to remind your students to explain why they included the evidence in their arguments and make the assumptions underlying their analysis and interpretation of the data explicit in order to provide an adequate justification of their evidence.

Reflecting on Ways to Design Better Investigations

It is important for students to reflect on the strengths and weaknesses of the investigation they designed during the explicit and reflective discussion. Students should therefore be encouraged to discuss ways to eliminate potential flaws, measurement errors, or sources of uncertainty in their investigations. To help students be more reflective about the design of their investigation and what they can do to make their investigations more rigorous in the future, you can ask them the following questions:

1. What were some of the strengths of the way you planned and carried out your investigation? In other words, what made it scientific?
2. What were some of the weaknesses of the way you planned and carried out your investigation? In other words, what made it less scientific?
3. What rules can we make, as a class, to ensure that our next investigation is more scientific?

Reflecting on the Nature of Scientific Knowledge and Scientific Inquiry

This investigation can be used to illustrate two important concepts related to the nature of scientific knowledge and the nature of scientific inquiry: (a) how scientific knowledge changes over time and (b) the difference between laws and theories in science (see Appendix 2 for a brief description of these two concepts). Be sure to review these concepts during and at the end of the explicit and reflective discussion. To help students think about these concepts in relation to what they did during the lab, you can ask them the following questions:

1. Scientific knowledge can and does change over time. Can you tell me why it changes?
2. Can you work with your group to come up some examples of how scientific knowledge has changed over time? Be ready to share in a few minutes.
3. Is the work-energy theorem an example of a law or a theory? Why?
4. Can you work with your group to come up with a rule that you can use to decide if something is a law or a theory? Be ready to share in a few minutes.

You can also use presentation software or other techniques to encourage your students to think about these concepts. You can show examples of how our thinking about energy has changed over time and ask students to discuss what they think led to those changes. You can also show examples of either a law (such as $PE_{grav} = m\mathbf{gh}$) or a theory (such as *gravity is the curvature of four-dimensional space-time due to the presence of mass*) and ask students to indicate if they think it is law or a theory and why.

Be sure to remind your students that, to be proficient in science, it is important that they understand what counts as scientific knowledge and how that knowledge develops over time.

Hints for Implementing the Lab

- We recommend the use of video analysis in this lab, because there are numerous assumptions about the motion that are used to simplify the mathematics and isolate important variables but that contribute to a mismatch between the predicted and observed results. The use of video analysis will allow students to isolate different parts of the motion and analyze data for each part independently. For example, video analysis software will allow students to analyze the motion of the ball rolling down the ramp separate from the motion of the ball in the cup. This will increase the precision of their measurements.
- Allowing students to design their own procedures for collecting data gives students an opportunity to try, to fail, and to learn from their mistakes. However, you can scaffold students as they develop their procedure by having them fill out an investigation proposal. These proposals provide a way for you to offer students hints and suggestions without telling them how to do it. You can also check the proposals quickly during a class period. For this lab we suggest using Investigation Proposal A.
- To minimize friction as much as possible, use smooth PVC pipe for the ball to roll down and a smooth floor surface for the cup to move.
- You may want to use two-sided tape on the inside of the cup so when the ball comes into contact with the inside of the cup, it sticks and the recoiling and subsequent second collision with the cup is minimized.
- Allow the students to become familiar with the equipment and materials as part of the tool talk before they begin to design their investigation. Giving them 5–10 minutes to examine the equipment and materials will let them see what they can and cannot do with them. This also gives students a chance to begin thinking about what variables to test and how to control for other variables.
- You may want to have students use mathematics when they are developing their rules to explain and predict the motion of a ball at the bottom of a ramp and the distance a cup moves after the ball rolls down the ramp and enters the cup. This is a great opportunity for them to practice building a function that models a relationship between two quantities. However, it is not required for this lab.
- Be sure to allow students to go back and re-collect data at the end of the argumentation session. Students often realize that they made numerous mistakes when they were collecting data as a result of their discussions during the argumentation session. The students, as a result, will want a chance to re-collect

data, and the re-collection of data should be encouraged when time allows. This also offers an opportunity to discuss what scientists do when they realize a mistake is made inside the lab.

If students use video analysis

- We suggest allowing students to familiarize themselves with the video analysis software before they finalize the procedure for the investigation, especially if they have not used such software previously. This gives students an opportunity to learn how to work with the software and to improve the quality of the video they take.
- Remind students to hold the video camera as still as possible. Any movement of the camera will introduce error into their analysis. If using actual camcorders, we recommend using a tripod to hold the camera steady. If students are using a camera on a cell phone or tablet, we recommend using a table to help steady the camera.
- Remind students to place a meterstick in the same field of view as the motion they are capturing with the video camera. Also, the meterstick should be approximately the same distance from the camera as the motion. Most video analysis software requires the user to define a scale in the video (this allows the software to establish distances and, subsequently, other variables dependent on distance and displacement).

Connections to Standards

Table 20.2 (p. 442) highlights how the investigation can be used to address learning objectives from AP Physics 1; learning objectives from AP Physics C: Mechanics, *Common Core State Standards*, in English language arts (*CCSS ELA*); and *Common Core State Standards*, Mathematics (*CCSS Mathematics*).

TABLE 20.2

Lab 20 alignment with standards

***NGSS* performance expectations**	• None
AP Physics 1 learning objectives	• 3.A.1.1: The student is able to express the motion of an object using narrative, mathematical, and graphical representations. • 3.A.1.2: The student is able to design an experimental investigation of the motion of an object. • 3.A.1.3: The student is able to analyze experimental data describing the motion of an object and is able to express the results of the analysis using narrative, mathematical, and graphical representations. • 4.C.1.2: The student is able to predict changes in the total energy of a system due to changes in position and speed of objects or frictional interactions within the system. • 5.B.1.2: The student is able to translate between a representation of a single object, which can only have kinetic energy, and a system that includes the object, which may have both kinetic and potential energies. • 5.B.3.2: The student is able to make quantitative calculations of the internal potential energy of a system from a description or diagram of that system. • 5.B.3.3: The student is able to apply mathematical reasoning to create a description of the internal potential energy of a system from a description or diagram of the objects and interactions in that system.
AP Physics C: Mechanics learning objectives	• I.C.1.b(3): Apply the theorem to determine the change in an object's kinetic energy and speed that results from the application of specified forces, or to determine the force that is required in order to bring an object to rest in a specified distance. • I.C.2.b(5): Calculate the potential energy of one or more objects in a uniform gravitational field. • I.C.3.c: Students should be able to recognize and solve problems that call for application both of conservation of energy and Newton's Laws.
Literacy connections (*CCSS ELA*)	• *Reading:* Key ideas and details, craft and structure, integration of knowledge and ideas • *Writing:* Text types and purposes, production and distribution of writing, research to build and present knowledge, range of writing • *Speaking and listening:* Comprehension and collaboration, presentation of knowledge and ideas

Mathematics connections (*CCSS Mathematics*)	• *Mathematical practices:* Reason abstractly and quantitatively, construct viable arguments and critique the reasoning of others, use appropriate tools strategically, attend to precision • *Number and quantity:* Reason quantitatively and use units to solve problems, represent and model with vector quantities, perform operations on vectors • *Algebra:* Interpret the structure of expressions, create equations that describe numbers or relationships, understand solving equations as a process of reasoning and explain the reasoning, solve equations and inequalities in one variable, represent and solve equations and inequalities graphically • *Functions:* Understand the concept of a function and use function notation, interpret functions that arise in applications in terms of the context, analyze functions using different representations, build a function that models a relationship between two quantities, interpret expressions for functions in terms of the situation they model • *Statistics and probability:* Summarize, represent, and interpret data on two categorical and quantitative variables; understand and evaluate random processes underlying statistical experiments; make inferences and justify conclusions from sample surveys, experiments, and observational studies

Lab Handout

Lab 20. Kinetic and Potential Energy: How Can We Use the Work-Energy Theorem to Explain and Predict Behavior of a System That Consists of a Ball, a Ramp, and a Cup?

Introduction

You have learned how to use Newton's laws of motion to explain how objects move and to predict the motion of an object over time. Newton's laws of motion therefore function as a useful model that people can use to understand how the world works and to predict how different objects move after they interact with each other. Physicists, however, can use other models to explain and predict the motion of objects and to help understand natural phenomena. One such model views the motion of objects through a lens of work and energy. This model is called the *work-energy theorem.* To understand how work and energy can be used to explain and predict motion, it is important to understand the basic assumptions underlying the work-energy theorem.

The first basic assumption of the work-energy theorem is that an object can store energy as the result of its position. This stored energy is called *potential energy.* The second basic assumption of the work-energy theorem is that all objects in motion have energy because they are moving. The energy of motion is called *kinetic energy.* There are many forms of kinetic energy, including vibrational (the energy due to vibrational motion), rotational (the energy due to rotational motion), and translational (the energy due to motion from one location to another). The third assumption of the work-energy theorem is that doing work on an object results in a change in the *mechanical energy* of that object. Mechanical energy is the sum of the potential and kinetic energy of an object. A change in mechanical energy of an object can result from adding energy to an object, taking away energy from an object, or changing the type of energy an object has from one form to another. Work is done on an object when a force acts on an object over a displacement. Therefore, *work* is mathematically defined as the product of the force acting on an object times the displacement. The fourth, and final, basic assumption of the work-energy theorem is that energy cannot be created or destroyed—it just changes form as objects move or as it transfers from one object to another one.

In this investigation you will have an opportunity to explore the relationship between potential energy, kinetic energy, mechanical energy, work, and displacement in terms of the motion of objects. To explore the relationship between these various components of the work-energy theorem, you will study a simple system that consists of a ball, a ramp, and a cup. You goal is to develop a set of rules that you can use to explain and predict the motion of the ball at the bottom of the ramp and the distance the cup moves after the ball rolls down the ramp and enters the cup. To be valid or acceptable, your set of rules must be consistent with the basic assumptions underlying the work-energy theorem outlined in this section.

Your Task

Use what you know about the work-energy theorem and the importance of tracking matter and energy in a system to develop a conceptual model (i.e., a set of rules) that will allow you to explain and predict the behavior of a system that consists of a ball, a ramp, and a cup. To develop your model, you will need to design and carry out several experiments to determine how changes in several different components of the ball-ramp-cup system affect (1) the motion of the ball at the bottom of the ramp after it rolls down it and (2) the distance a cup moves when a ball is rolled down an incline and comes into contact with the cup. Once you have developed your rules, you will need to test them to determine if you can use them to make accurate predictions about the behavior of the ball-ramp-cup system.

The guiding question of this investigation is, ***How can we use the work-energy theorem to explain and predict behavior of a system that consists of a ball, a ramp, and a cup?***

Materials

You may use any of the following materials during your investigation:

- Safety glasses or goggles (required)
- Support stand
- Extension clamp
- Set of 25 mm balls (includes brass, aluminum, steel, cork, wood, and copper)
- PVC pipe
- Electronic or triple beam balance
- Plastic cup
- 2 Metersticks
- Protractor
- Stopwatch

If you have access to the following equipment, you may also consider using a video camera and a computer or tablet with video analysis software.

Safety Precautions

Follow all normal lab safety rules. In addition, take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Wash hands with soap and water after completing the lab.

LAB 20

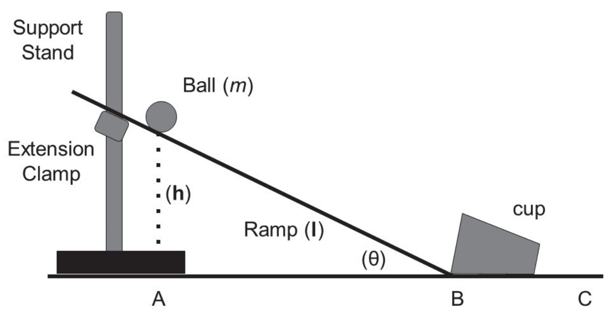
Investigation Proposal Required? ☐ Yes ☐ No

Getting Started

Your first step in this investigation is to design and carry several experiments to determine how changes in several different components of the ball-ramp-cup system affect (1) the motion of the ball at the bottom of the ramp after it rolls down it and (2) the distance a cup moves when a ball is rolled down an incline and comes into contact with the cup. Figure L20.1 shows how you can set up the ball-ramp-cup system. The components of the system that you can change include the mass of the ball (*m*), the height of the ramp (**h**), the length of the ramp (**l**), and the angle of inclination (θ). Before you design or carry out your experiments, however, you must first determine what type of data you need to collect, how you will collect it, and how you will analyze it.

FIGURE L20.1

The ball-ramp-cup system



To determine *what type of data you need to collect,* think about the following questions:

- What are the boundaries and components of the system under study?
- How will you quantify the amount of potential, kinetic, and mechanical energy in the system?
- How can you track the potential, kinetic, and mechanical energy changes within this system?
- Which factors might control rates of change in the system under study?
- What will be the independent variable and the dependent variable for each experiment?

To determine *how you will collect your data,* think about the following questions:

- What other variables will you need to control in each experiment?
- What will be the reference point for measurement?

- What measurement scale or scales should you use to collect data?
- What equipment will you need to take your various measurements?
- How will you make sure that your data are of high quality (i.e., how will you reduce error)?
- How will you keep track of and organize the data you collect?

To determine *how you will analyze your data*, think about the following questions:

- What type of calculations will you need to make?
- How could you use mathematics to describe a relationship between variables?
- What types of comparisons will be useful?
- What type of table or graph could you create to help make sense of your data?

Once you have determined how changes in the different components of the ball-ramp-cup system affect (1) the motion of the ball at the bottom of the ramp after it rolls down it and (2) the distance a cup moves when a ball is rolled down an incline and comes into contact with the cup, your group will need to develop a set of rules that you can use to explain and predict the behavior of this system. Your set of rules must be consistent with the four basic assumptions underlying the work-energy theorem outlined in the "Introduction."

The last step in this investigation will be to test your model. To accomplish this goal, you can set components of the system to values that you did not test (e.g., if you tested the height of the ramp at 0.5 m and 0.75 m, then set the height to 0.6 m) to determine if you can use your rulesto make accurate predictions, then you will be able to generate the evidence you need to convince others that your rules are a valid way to explain and predict behavior of the ball and the cup in terms of the work-energy theorem of motion.

Connections to the Nature of Scientific Knowledge and Scientific Inquiry

As you work through your investigation, you may want to consider

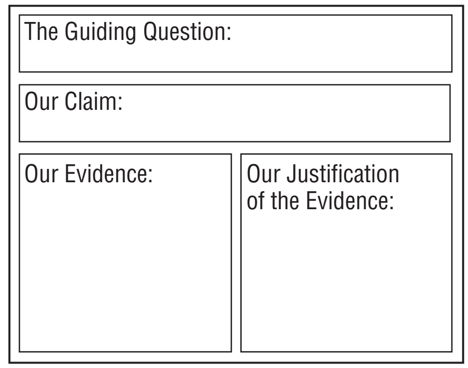
- how scientific knowledge changes over time, and
- the difference between laws and theories in science.

Initial Argument

Once your group has finished collecting and analyzing your data, your group will need to develop an initial argument. Your initial argument must include a claim, evidence to support your claim, and a *justification* of the evidence. The *claim* is your group's answer to the guiding question. The *evidence* is an analysis and interpretation of your data. Finally, the *justification* of the evidence is why your group thinks the evidence matters. The justification of the evidence is important because scientists can use different kinds of evidence to support their claims. You group will create your initial argument on a whiteboard. Your whiteboard should include all the information shown in Figure L20.2.

FIGURE L20.2

Argument presentation on a whiteboard



Argumentation Session

The argumentation session allows all of the groups to share their arguments. One or two members of each group will stay at the lab station to share that group's argument, while the other members of the group go to the other lab stations to listen to and critique the other arguments. This is similar to what scientists do when they propose, support, evaluate, and refine new ideas during a poster session at a conference. If you are presenting your group's argument, your goal is to share your ideas and answer questions. You should also keep a record of the critiques and suggestions made by your classmates so you can use this feedback to make your initial argument stronger. You can keep track of specific critiques and suggestions for improvement that your classmates mention in the space below.

Critiques about our initial argument and suggestions for improvement:

If you are critiquing your classmates' arguments, your goal is to look for mistakes in their arguments and offer suggestions for improvement so these mistakes can be fixed. You should look for ways to make your initial argument stronger by looking for things that the other groups did well. You can keep track of interesting ideas that you see and hear during the argumentation in the space below. You can also use this space to keep track of any questions that you will need to discuss with your team.

Interesting ideas from other groups or questions to take back to my group:

Once the argumentation session is complete, you will have a chance to meet with your group and revise your initial argument. Your group might need to gather more data or design a way to test one or more alternative claims as part of this process. Remember, your goal at this stage of the investigation is to develop the best argument possible.

Report

Once you have completed your research, you will need to prepare an *investigation report* that consists of three sections. Each section should provide an answer to the following questions:

1. What question were you trying to answer and why?
2. What did you do to answer your question and why?
3. What is your argument?

Your report should answer these questions in two pages or less. This report must be typed, and any diagrams, figures, or tables should be embedded into the document. Be sure to write in a persuasive style; you are trying to convince others that your claim is acceptable or valid!

Checkout Questions

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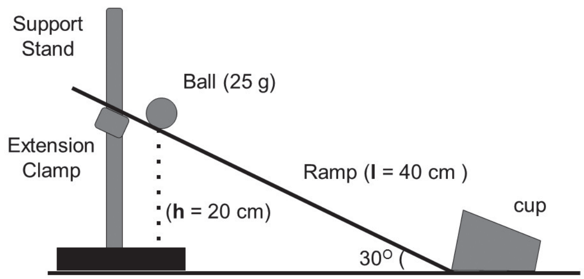
Use the figure below to answer questions 1 and 2. For the acceleration due to gravity, use the positive value for **g** (9.8 m/sec^2).



1. What is the potential energy of the ball at the moment it is released on the incline?

   How do you know?

2. What is the kinetic energy of the ball at the moment it strikes the cup?

   How do you know?

3. Galileo hypothesized that free objects accelerate uniformly, or stated another way, that a falling object's velocity increases an equal amount in each equal time interval. Explain how the results of this ball and cup experiment could be used in support of this claim.

4. There is a difference between a law and a theory in science.

    a. I agree with this statement.
    b. I disagree with this statement.

    Explain your answer, using an example from your investigation about kinetic and potential energy.

5. Scientific knowledge, once proven to be true, does not change.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about kinetic and potential energy.

6. Scientists often need to identify a system and then create a model of it as part of an investigation. Explain why it useful to create models of systems, using an example from your investigation about kinetic and potential energy and an example from previous investigations in this class or your previous science classes.

7. One of the important aims in science is to track how energy and matter move within a system and to determine if the energy and matter within the system are conserved. Explain why it is useful to track how energy and matter move within a system, using an example from your investigation about kinetic and potential energy and an example from previous investigations in this class or your previous science classes.

Teacher Notes

Lab 21. Conservation of Energy and Pendulums: How Does Placing a Nail in the Path of a Pendulum Affect the Height of a Pendulum Swing?

Purpose

The purpose of this lab is to *introduce* students to the disciplinary core idea (DCI) of Energy from the *NGSS* by giving them an opportunity to determine how placing a nail in the path of a pendulum affects the height of a pendulum swing. This lab also gives students an opportunity to learn about the crosscutting concepts (CCs) of (a) Patterns; (b) Cause and Effect: Mechanism and Explanation; and (c) Energy and Matter: Flows, Cycles, and Conservation from the *NGSS.* In addition, this lab can be used to help students understand three big ideas from AP Physics: (a) objects and systems have properties such as mass or charge, (b) the interactions of an object with other objects can be described by forces, and (c) changes that occur as result of interactions are constrained by conservation laws. As part of the explicit and reflective discussion, students will also learn about (a) the difference between observations and inferences in science and (b) how scientific knowledge can change over time.

Underlying Physics Concepts

The law of conservation of energy states that in a closed system the total energy of the system remains constant. The total energy of an object is the sum total of the different types of energy possessed by the object. This means that the total mechanical energy (*ME*) of an object is the sum of its potential energy (PE) and kinetic energy (KE), as shown in Equation 21.1.

(Equation 21.1) $ME = \mathrm{PE} + \mathrm{KE}$

The potential energy and kinetic energy of the pendulum can be found in Equations 21.2 and 21.3, where m is the mass of the pendulum bob, $\mathbf{g}$ is the acceleration due to gravity and is a constant 9.8 m/s^2, $\mathbf{h}$ is the height above the equilibrium point, and $\mathbf{v}$ is the velocity of the pendulum at any given point. In SI units, mass is measured in kilograms (kg), height is measured in meters (m), and velocity is measured in meters per second (m/s).

(Equation 21.2) $\mathrm{PE} = m\mathbf{gh}$

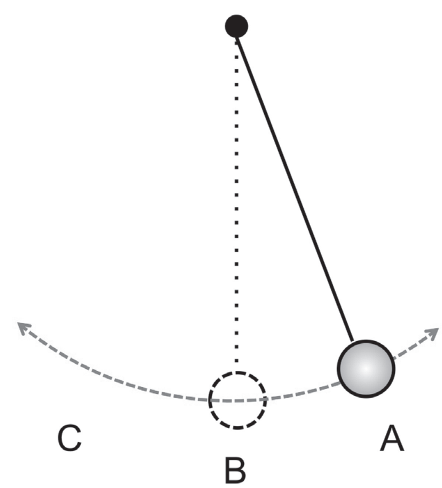
(Equation 21.3) $\mathrm{KE} = \frac{1}{2} m\mathbf{v}^2$

As the pendulum swings, there are three important points, shown in Figure 21.1. Point A is the release point of the pendulum and is some height above point B. Because the pendulum mass does have a height relative to point B, the pendulum has potential energy. At point A, the velocity of the mass on the end of the pendulum is zero. Pursuant to Equation 21.3, if the velocity of an object is zero, the kinetic energy of that object is also equal to zero.

Equation 21.1 suggests that the total mechanical energy of the system is equal to the sum of the potential energy and kinetic energy. At point A, this means $ME = \mathrm{PE_A} + \mathrm{KE_A}$. We have established that the kinetic energy of the pendulum is zero at point A, so the total mechanical energy of the pendulum is equal to the potential energy at point A.

FIGURE 21.1

A pendulum



Point B is referred to as the equilibrium point, because at point B there is no net force acting on the pendulum mass. For a pendulum, point B is also defined as "ground level" for the height of the mass. In other words, $\mathbf{h} = 0$ at point B. Pursuant to Equation 21.2, this means that the potential energy at point B is equal to zero. The velocity of the pendulum is maximum at point B, and as such, the kinetic energy is also a maximum. Furthermore, if the potential energy at point B is equal to zero, then the kinetic energy at point B is equal to the potential energy at point A.

As the pendulum passes through the equilibrium point, it will continue to swing, reach a maximum height at point C, and then swing back toward the equilibrium point. At point C, the velocity of the pendulum mass is equal to zero. We can show this conceptually as follows: Before reaching point C, the mass had a negative, non-zero velocity to the left. After it begins to swing back toward equilibrium, the pendulum has a positive, non-zero velocity to the right. Because the velocity is a continuous function with respect to time, when it accelerates from a negative to a positive velocity, there must be a point where the velocity is equal to zero.

If the velocity is equal to zero, then the total mechanical energy of the pendulum at point C is equal to the potential energy at point C. As we have already established, the total mechanical energy of the system is equal to the potential energy of the pendulum at point A. Thus, the potential energy at point C is equal to the potential energy at point A, shown mathematically in Equation 21.4.

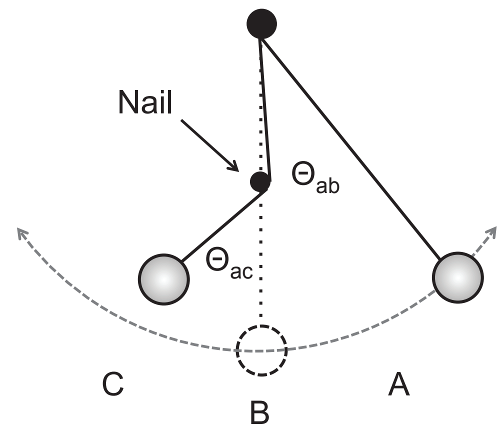
$$\textbf{(Equation 21.4)}\quad m\mathbf{gh}_\mathrm{A} = m\mathbf{gh}_\mathrm{C}$$

Because the mass of the ball does not change as the pendulum swings, and the acceleration due to gravity is constant, the height at point C must also be equal to the height at point A.

In this lab, students will place a nail in the path of the pendulum to determine how the nail affects the height of the swing (shown in Figure 21.2). Despite placing the nail in the path of the pendulum, the height of the mass above the pendulum swing remains the same, as shown in Equation 21.4 (with the one caveat that the initial release point must be lower than the height of the nail). However, the angle the swing makes with respect to the equilibrium point does change. In Figure 21.2, the measure of angle ac is always greater than the measure of angle ab (as long as the nail is above the release point). Finally, the discussion thus far has ignored the role or air resistance on the motion of the pendulum bob as it swings, because this simplifies the mathematical analysis of the motion. Although the air resistance on the pendulum in motion will eventually bring the pendulum to rest, through one swing it should be that the height after contact with the nail is equal to that of the release height.

FIGURE 21.2

The angles formed by the pendulum



Timeline

The instructional time needed to complete this lab investigation is 170–230 minutes. Appendix 3 (p. 531) provides options for implementing this lab investigation over several class periods. Option C (230 minutes) should be used if students are unfamiliar with scientific writing, because this option provides extra instructional time for scaffolding the writing process. You can scaffold the writing process by modeling, providing examples, and providing hints as students write each section of the report. Option C can also be used if you are introducing students to the video analysis programs. Option D (170 minutes) should be used if students are familiar with scientific writing and have developed the skills needed to write an investigation report on their own. In option D, students complete stage 6 (writing the investigation report) and stage 8 (revising the investigation report) as homework.

Materials and Preparation

The materials needed to implement this investigation are listed in Table 21.1. The items can be purchased from a science supply company such as Carolina, Flinn Scientific, PASCO, Vernier, or Ward's Science. The video analysis software can be purchased from Vernier (Logger *Pro*) or PASCO (SPARKvue or Capstone). These companies also have apps that can be used on Apple- or Android-based tablets and cell phones. We recommend consulting with your school's information technology coordinator to determine the best option for your students.

TABLE 21.1

Materials list for Lab 21

Item	Quantity
Safety glasses or goggles	1 per student
Video camera	1 per group
Computer or tablet with video analysis software	1 per group
Support stand	1 per group
Clamps	2 per group
Nail (3-inch framing)	1 per group
Hanging mass set	1 per group
String	As needed
Meterstick	1 per group
Investigation Proposal A (optional)	1 per group
Whiteboard, 2' × 3'*	1 per group
Lab Handout	1 per student
Peer-review guide and teacher scoring rubric	1 per student
Checkout Questions	1 per student

* As an alternative, students can use computer and presentation software such as Microsoft PowerPoint or Apple Keynote to create their arguments.

Be sure to use a set routine for distributing and collecting the materials during the lab investigation. One option is to set up the materials for each group at each group's lab station before class begins. This option works well when there is a dedicated section of the classroom for lab work and the materials are large and difficult to move (such as a dynamics track). A second option is to have all the materials on a table or cart at a central location. You can then assign a member of each group to be the "materials manager." This individual is responsible for collecting all the materials his or her group needs from the table or cart during class and for returning all the materials at the end of the class. This option works well when the materials are small and easy to move (such as stopwatches, metersticks, or hanging masses). It also makes it easy to inventory the materials at the end of the class before students leave for the day.

Safety Precautions

Remind students to follow all normal lab safety rules. In addition, tell students to take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Handle nails with care. Nail ends can be sharp and can puncture or scrape skin.
3. Keep fingers and toes out of the way of moving objects.
4. Wash hands with soap and water after completing the lab.

Topics for the Explicit and Reflective Discussion

Reflecting on the Use of Core Ideas and Crosscutting Concepts During the Investigation

Teachers should begin the explicit and reflective discussion by asking students to discuss what they know about the core idea they used during the investigation. The following are some important concepts related to the core idea of Energy that students will need to determine how placing a nail in the path of a pendulum affects the height of a pendulum swing:

- Energy is conserved in all systems under all circumstances.
- Conserved quantities are constant in an isolated or a closed system. An *open system* is one that exchanges any conserved quantity with its surroundings.
- The mechanical energy of a system includes the kinetic energy of the objects that make up the system and the potential energy of the configuration of the objects that make up the system.
- Changes in the potential energy of a system can result in changes to the kinetic energy system because energy is constant in a closed system.

To help students reflect on what they know about energy, we recommend showing them two or three images using presentation software that help illustrate these important ideas. You can then ask the students the following questions to encourage them to share how they are thinking about these important concepts:

1. What do we see going on in this image?
2. Does anyone have anything else to add?
3. What might be going on that we can't see?
4. What are some things that we are not sure about here?

You can then encourage students to think about how CCs played a role in their investigation. There are at least three CCs that students need to determine how placing a nail in the path of a pendulum affects the height of a pendulum swing: (a) Patterns; (b) Cause and Effect: Mechanism and Explanation; and (c) Energy and Matter: Flows, Cycles, and Conservation (see Appendix 2 [p. 527] for a brief description of these CCs). To help students reflect on what they know about these CCs, we recommend asking them the following questions:

1. Why is it important to look for patterns during an investigation?
2. What patterns did you identify during your investigation? What did the identification of these patterns allow you to do?
3. Why is it important to identify causal relationships in science?
4. What did you have to do during your investigation to determine what causes a change in the height of a pendulum swing? Why was that useful to do?
5. Scientists often attempt to track how energy and matter move into, out of, and within systems as part of an investigation. Why is this useful?
6. How did you attempt to track how energy moves within the system you were studying? What did tracking energy allow you to do during your investigation?

You can then encourage the students to think about how they used all these different concepts to help answer the guiding question and why it is important to use these ideas to help justify their evidence for their final arguments. Be sure to remind your students to explain why they included the evidence in their arguments and make the assumptions underlying their analysis and interpretation of the data explicit in order to provide an adequate justification of their evidence.

Reflecting on Ways to Design Better Investigations

It is important for students to reflect on the strengths and weaknesses of the investigation they designed during the explicit and reflective discussion. Students should therefore be encouraged to discuss ways to eliminate potential flaws, measurement errors, or sources of uncertainty in their investigations. To help students be more reflective about the design of their investigation and what they can do to make their investigations more rigorous in the future, you can ask them the following questions:

1. What were some of the strengths of the way you planned and carried out your investigation? In other words, what made it scientific?
2. What were some of the weaknesses of the way you planned and carried out your investigation? In other words, what made it less scientific?
3. What rules can we make, as a class, to ensure that our next investigation is more scientific?

Reflecting on the Nature of Scientific Knowledge and Scientific Inquiry

This investigation can be used to illustrate two important concepts related to the nature of scientific knowledge and the nature of scientific inquiry: (a) the difference between observations and inferences in science and (b) how scientific knowledge changes over time (see Appendix 2 for a brief description of these two concepts). Be sure to review these concepts during and at the end of the explicit and reflective discussion. To help students think about these concepts in relation to what they did during the lab, you can ask them the following questions:

1. You had to make observations and inferences during your investigation. Can you give me some examples of these observations and inferences?
2. Can you work with your group to come up with a rule that you can use to decide if a piece of information is an observation or an inference? Be ready to share in a few minutes.
3. Scientific knowledge can and does change over time. Can you tell me why it changes?
4. Can you work with your group to come up some examples of how scientific knowledge has changed over time? Be ready to share in a few minutes.

You can also use presentation software or other techniques to encourage your students to think about these concepts. You can show examples of information from the investigation that are either observations or inferences and ask students to classify each example and explain their thinking. You can also show examples of how our thinking about energy has changed over time and ask students to discuss what they think led to those changes.

Be sure to remind your students that, to be proficient in science, it is important that they understand what counts as scientific knowledge and how that knowledge develops over time.

Hints for Implementing the Lab

- Allowing students to design their own procedures for collecting data gives students an opportunity to try, to fail, and to learn from their mistakes. However, you can scaffold students as they develop their procedure by having them fill out an investigation proposal. These proposals provide a way for you to offer students hints and suggestions without telling them how to do it. You can also check the proposals quickly during a class period. For this lab we suggest using Investigation Proposal A.
- For optimal results, make the support stand and associated setup as rigid as possible. A pendulum length of 1 m or more is also useful.
- If the release point of the pendulum is above the height of the nail, the pendulum will swing and wrap around the nail. For best results, remind students to release the pendulum from a point below the height of the nail.
- Allow the students to become familiar with the equipment and materials, including the video analysis software, as part of the tool talk before they begin to design their investigation. Giving them 5–10 minutes to examine the equipment

and materials will let them see what they can and cannot do with them. This also gives students a chance to begin thinking about what variables to test and how to control for other variables.

- Remind students to hold the video camera as still as possible. Any movement of the camera will introduce error into their analysis. If using actual camcorders, we recommend using a tripod to hold the camera steady. If students are using a camera on a cell phone or tablet, we recommend using a table to help steady the camera.
- Remind students to place a meterstick in the same field of view as the motion they are capturing with the video camera. Also, the meterstick should be approximately the same distance from the camera as the motion. Most video analysis software requires the user to define a scale in the video (this allows the software to establish distances and, subsequently, other variables dependent on distance and displacement).
- Be sure to allow students to go back and re-collect data at the end of the argumentation session. Students often realize that they made numerous mistakes when they were collecting data as a result of their discussions during the argumentation session. The students, as a result, will want a chance to re-collect data, and the re-collection of data should be encouraged when time allows. This also offers an opportunity to discuss what scientists do when they realize a mistake is made inside the lab.

Connections to Standards

Table 21.2 (p. 462) highlights how the investigation can be used to address learning objectives from AP Physics 1; learning objectives from AP Physics C: Mechanics, *Common Core State Standards,* in English language arts (*CCSS ELA*); and *Common Core State Standards,* Mathematics (*CCSS Mathematics*).

TABLE 21.2

Lab 21 alignment with standards

***NGSS* performance expectations**	• None
AP Physics 1 learning objectives	• 3.A.1.1: The student is able to express the motion of an object using narrative, mathematical, and graphical representations. • 3.A.1.2: The student is able to design an experimental investigation of the motion of an object. • 3.A.1.3: The student is able to analyze experimental data describing the motion of an object and is able to express the results of the analysis using narrative, mathematical, and graphical representations. • 4.C.1.2: The student is able to predict changes in the total energy of a system due to changes in position and speed of objects or frictional interactions within the system. • 5.B.1.2: The student is able to translate between a representation of a single object, which can only have kinetic energy, and a system that includes the object, which may have both kinetic and potential energies. • 5.B.3.2: The student is able to make quantitative calculations of the internal potential energy of a system from a description or diagram of that system. • 5.B.3.3: The student is able to apply mathematical reasoning to create a description of the internal potential energy of a system from a description or diagram of the objects and interactions in that system.
AP Physics C: Mechanics learning objectives	• I.C.3.c: Students should be able to recognize and solve problems that call for application both of conservation of energy and Newton's laws. • I.C.3.a(3): Analyze situations in which an object's mechanical energy is changed by friction or by a specified externally applied force.
Literacy connections (*CCSS ELA*)	• *Reading:* Key ideas and details, craft and structure, integration of knowledge and ideas • *Writing:* Text types and purposes, production and distribution of writing, research to build and present knowledge, range of writing • *Speaking and listening:* Comprehension and collaboration, presentation of knowledge and ideas

Mathematics connections (*CCSS Mathematics*)	• *Mathematical practices:* Reason abstractly and quantitatively, construct viable arguments and critique the reasoning of others, use appropriate tools strategically, attend to precision • *Number and quantity:* Reason quantitatively and use units to solve problems, represent and model with vector quantities, perform operations on vectors • *Algebra:* Interpret the structure of expressions, understand solving equations as a process of reasoning and explain the reasoning, solve equations and inequalities in one variable, represent and solve equations and inequalities graphically. • *Functions:* Understand the concept of a function and use function notation, interpret functions that arise in applications in terms of the context, analyze functions using different representations, interpret expressions for functions in terms of the situation they model • *Statistics and probability:* Summarize, represent, and interpret data on two categorical and quantitative variables; understand and evaluate random processes underlying statistical experiments; make inferences and justify conclusions from sample surveys, experiments, and observational studies

Lab Handout

Lab 21. Conservation of Energy and Pendulums: How Does Placing a Nail in the Path of a Pendulum Affect the Height of a Pendulum Swing?

Introduction

Two of the most influential thinkers in history were Aristotle in the 4th century BC and Galileo in the 16th–17th centuries. Aristotle took a philosophical approach to understanding the natural world, whereas Galileo preferred a more empirical one. Thus, they developed some very different explanations about the motion of objects. For example, Aristotle claimed that heavier bodies fall faster than lighter ones in the same medium, whereas Galileo claimed that in a vacuum all bodies fall with the same speed.

Aristotle and Galileo also did not agree about the nature of energy. Historians of science attribute the first use of the word *energy* to Aristotle (in classical Greek, *energeia*). Historians debate what exactly Aristotle meant by the word *energeia,* with the most common translation being "activity or operation." Historians do agree, however, that Aristotle used the concept of energeia not only to analyze the motion of objects but also to understand ethics and psychology. According to Aristotle, a person's desire to be happy was a type of energeia. Galileo, on the other hand, provided a more modern view of energy and suggested that energy was a property of objects. Thus, he decoupled the term *energy* from the study of ethics or psychology.

Since Galileo's time, other physicists have contributed to our understanding of forces, motion, and energy. Isaac Newton, in the 17th and early 18th centuries, provided the mathematical foundation for the study of force and motion. In the 19th century, Thomas Young was the first to define *energy* in the formal sense, and Gaspard-Gustave de Coriolis expanded on Young's definition of energy by introducing the concept of kinetic energy. Also in the 19th century, William Rankine was the first to propose the idea of potential energy, and James Prescott Joule and William Thomson (better known as Lord Kelvin) developed the law of conservation of energy, which states that the total energy in a closed system remains constant. We now use these ideas about energy to help understand and explain a wide range of natural phenomena.

In this investigation, you will have an opportunity to use these important ideas about energy to explore the motion of a pendulum. The motion of a pendulum has been studied for hundreds of years. Galileo, for example, used the motion of a pendulum to help quantify his ideas about falling objects. Other scientists have also used the pendulum to investigate forces and energy. One of Galileo's most informative and important investigations about the behavior of a pendulum, however, was when he placed a nail in the path of a swinging pendulum as shown in Figure L21.1. This simple modification to a basic pendulum allowed Galileo to explore the energy of the pendulum bob as it swings back and forth.

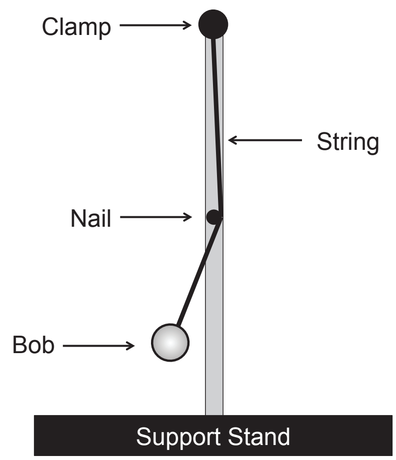
Your Task

Use what you know about energy, cause-and-effect relationships in science, and the importance of identifying and explaining patterns in nature to design and carry out an investigation to determine how the height of a pendulum swing changes after coming into contact with a nail in its path.

The guiding question of this investigation is, ***How does placing a nail in the path of a pendulum affect the height of a pendulum swing?***

FIGURE L21.1

Pendulum and nail setup



Materials

You may use any of the following materials during your investigation:

- Safety glasses or goggles (required)
- Video camera
- Computer or tablet with video analysis software
- Support stand Clamps Nail
- Hanging mass set
- String
- Meterstick

Safety Precautions

Follow all normal lab safety rules. In addition, take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Handle nails with care. Nail ends can be sharp and can puncture or scrape skin.
3. Keep fingers and toes out of the way of moving objects.
4. Wash hands with soap and water after completing the lab.

Investigation Proposal Required? ☐ Yes ☐ No

Getting Started

To answer the guiding question, you will need to design and carry out an investigation to determine how the height of a pendulum swing changes after the string comes into contact with a nail as the bob swings back and forth. Be sure to focus only on the height of a pendulum swing during the first few oscillations, because air resistance will cause the pendulum to eventually slow down and come to rest. It is also important to examine pendulums with different lengths of string and different bob masses during your investigation. With these issues in mind, you can now decide what type of data you need to collect, how you will collect it, and how you will analyze it.

To determine *what type of data you need to collect,* think about the following questions:

- What are the boundaries and components of the system you are studying?
- How can you describe the components of the system quantitatively?
- How could you keep track of changes in this system quantitatively?
- What could cause a change in the height of the pendulum swing?
- How will you determine the height of pendulum swing?
- Is it useful to track how energy flows into, out of, or within this system?
- What else will you need to measure during the investigation?

To determine *how you will collect the data*, think about the following questions:

- What type of research design needs to be used to establish a cause-and-effect relationship?
- How could you track the flow of energy within this system?
- How long will you need to observe the pendulum swinging back and forth?
- What types of comparisons will be useful?
- How will you vary the length of the string and the mass of the bob?
- What will be the reference point for your measurements?
- What equipment will you need to use in order to make the measurements you need?
- How will you make sure that your data are of high quality (i.e., how will you reduce error)?
- How will you keep track of and organize the data you collect?

To determine *how you will analyze the data,* think about the following questions:

- What types of patterns might you look for as you analyze your data?
- How could you use mathematics to determine if there is a difference between conditions?
- How precise is your video (frames per second)?
- What type of table or graph could you create to help make sense of your data?

Connections to the Nature of Scientific Knowledge and Scientific Inquiry

As you work through your investigation, you may want to consider

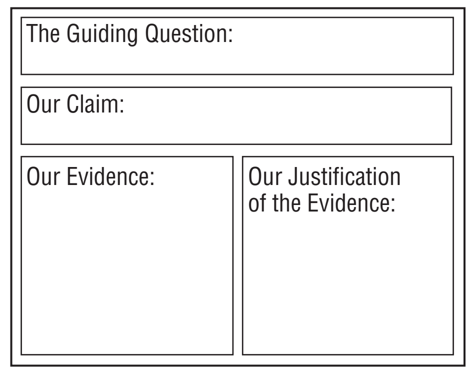
- the difference between observations and inferences in science, and
- how scientific knowledge changes over time.

Initial Argument

Once your group has finished collecting and analyzing your data, your group will need to develop an initial argument. Your argument must include a claim, evidence to support your claim, and a justification of the evidence. The *claim* is your group's answer to the guiding question. The *evidence* is an analysis and interpretation of your data. Finally, the *justification* of the evidence is why your group thinks the evidence matters. The justification of the evidence is important because scientists can use different kinds of evidence to support their claims. Your group will create your initial argument on a whiteboard. Your whiteboard should include all the information shown in Figure L21.2.

FIGURE L21.2

Argument presentation on a whiteboard



Argumentation Session

The argumentation session allows all of the groups to share their arguments. One or two members of each group will stay at the lab station to share that group's argument, while the other members of the group go to the other lab stations to listen to and critique the other arguments. This is similar to what scientists do when they propose, support, evaluate, and refine new ideas during a poster session at a conference. If you are presenting your group's argument, your goal is to share your ideas and answer questions. You should also keep a record of the critiques and suggestions made by your classmates so you can use this feedback to make your initial argument stronger. You can keep track of specific critiques and suggestions for improvement that your classmates mention in the space below.

Critiques about our initial argument and suggestions for improvement:

If you are critiquing your classmates' arguments, your goal is to look for mistakes in their arguments and offer suggestions for improvement so these mistakes can be fixed. You should look for ways to make your initial argument stronger by looking for things that the other groups did well. You can keep track of interesting ideas that you see and hear during the argumentation in the space below. You can also use this space to keep track of any questions that you will need to discuss with your team.

Interesting ideas from other groups or questions to take back to my group:

Once the argumentation session is complete, you will have a chance to meet with your group and revise your initial argument. Your group might need to gather more data or design a way to test one or more alternative claims as part of this process. Remember, your goal at this stage of the investigation is to develop the best argument possible.

Report

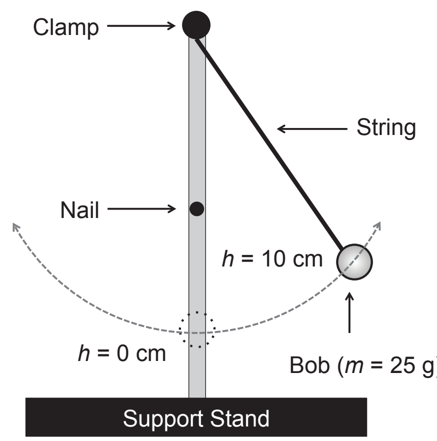
Once you have completed your research, you will need to prepare an *investigation report* that consists of three sections. Each section should provide an answer to the following questions:

1. What question were you trying to answer and why?
2. What did you do to answer your question and why?
3. What is your argument?

Your report should answer these questions in two pages or less. This report must be typed, and any diagrams, figures, or tables should be embedded into the document. Be sure to write in a persuasive style; you are trying to convince others that your claim is acceptable or valid!

Checkout Questions

Lab 21. Conservation of Energy and Pendulums: How Does Placing a Nail in the Path of a Pendulum Affect the Height of a Pendulum Swing?



1. Pictured at right is a pendulum. Let **h** = 0 represent the height when the bob is at equilibrium and acceleration due to gravity is 9.8 m/s^2 With these facts, calculate the kinetic energy of the bob when it is at the equilibrium position, assuming the pendulum is released from the point where **h** = 10 cm.

2. The length of the pendulum has an effect on the height of the bob after contacting and sweeping through the nail (assuming the initial height is not higher than the nail).

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using the findings from your investigation about placing a nail in the path of a pendulum.

3. There is no difference between observations and inferences in science.
   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about placing a nail in the path of a pendulum.

4. Scientific knowledge can change over time.
   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about placing a nail in the path of a pendulum.

5. Scientists often look for or attempt to identify patterns in nature. Explain why this is a useful practice, using an example from your investigation about placing a nail in the path of a pendulum.

6. In science, understanding cause-and-effect relationships is an important goal. Sometimes, scientists hypothesize a causal relationship that is not supported by the data. Does this mean there was something wrong with the investigation? Explain your answer, using an example from your investigation about placing a nail in the path of a pendulum.

7. In a pendulum, energy is transferred from potential to kinetic energy. Discuss the relationship between the potential and kinetic energy of the pendulum as it swings back and forth. Is energy conserved? Why is it important to keep track of the energy as it is transferred from potential to kinetic energy?

LAB 22

Teacher Notes

Lab 22. Conservation of Energy and Wind Turbines: How Can We Maximize the Amount of Electrical Energy That Will Be Generated by a Wind Turbine Based on the Design of Its Blades?

Purpose

The purpose of this lab is to *introduce* students to the disciplinary core idea (DCI) of Energy from the *NGSS* by giving them an opportunity to determine how to maximize the amount of electrical energy produced by a wind turbine. This lab also gives students an opportunity to learn about the crosscutting concepts (CCs) of (a) Systems and System Models; (b) Energy and Matter: Flows, Cycles, and Conservation; and (c) Structure and Function from the *NGSS.* In addition, this lab can be used to help students understand four big ideas from AP Physics: (a) objects and systems have properties such as mass or charge, (b) the interactions of an object with other objects can be described by forces, (c) interactions between systems can result in changes in those systems, and (d) changes that occur as result of interactions are constrained by conservation laws. As part of the explicit and reflective discussion, students will also learn about (a) how scientific knowledge changes over time and (b) how the culture of science, societal needs, and current events influence the work of scientists.

Underlying Physics Concepts

Wind turbines work by converting the translational kinetic energy of wind particles to the rotational kinetic energy of the wind turbine. The rotational kinetic energy of the wind turbine is then converted to electrical energy by an induction generator. An induction generator works by manually turning a rotor that is attached to a wire. The wire rotates in a magnetic field, thereby producing an alternating current. In this way, the kinetic energy of wind particles can be converted into electrical energy.

It is important to note that the energy conversions are not 100% efficient. That is, energy is not completely converted from one form to the other. Some energy is lost as heat due to friction when the rotor is spinning. Furthermore, the collisions between the wind particles and the turbine blades are not elastic, so kinetic energy is not conserved during the collision (the total energy is conserved, but some kinetic energy may be lost as heat).

When analyzing a collision, it is always best to start with momentum, because the momentum of the system is always conserved (momentum is not lost to the surroundings). We can therefore ask, How is the translational momentum of the wind transferred to angular momentum of the turbine? Assuming the strength of the current generated is a function of the angular velocity of the rotor, then it is also possible to answer this question based on the induced angular momentum of the turbine's blades. Furthermore, if we assume that the wind blows at a constant speed and the density of the air remains constant (valid assumptions when using a fan to produce the wind in a controlled lab setting), then the translational momentum of the wind remains constant. This means that the angular momentum of the wind turbine is a function of the design of the turbine. For this lab, the relationship of the design of the turbine to the induced angular momentum of the turbine is overshadowed by the relationship between the design of the turbine and the electrical energy produced by the turbine. That being said, the angular momentum of the turbine mediates the relationship between the kinetic energy of the wind and the electrical energy produced by the turbine.

In this lab, students must investigate various factors that affect the induced angular momentum of the turbine and the resultant production of electrical energy. In the Lab Handout we identify several possible factors that affect the electrical energy produced by the wind turbine. These factors include the angle of the blade relative to the wind, the shape of the blade, and the number of blades on the turbine. This is not meant to be an exhaustive list, and students may choose to investigate other potential variables. In general, the angle of the blade with respect to the wind that will produce a maximum energy output is approximately 20°. It is important to note, however, that other factors, such as the wind speed, will affect the exact angle that produces maximum energy output.

Timeline

The instructional time needed to complete this lab investigation is 220–280 minutes. Appendix 3 (p. 531) provides options for implementing this lab investigation over several class periods. Option A (280 minutes) should be used if students are unfamiliar with scientific writing, because this option provides extra instructional time for scaffolding the writing process. You can scaffold the writing process by modeling, providing examples, and providing hints as students write each section of the report. Option B (220 minutes) should be used if students are familiar with scientific writing and have developed the skills needed to write an investigation report on their own. In option B, students complete stage 6 (writing the investigation report) and stage 8 (revising the investigation report) as homework.

Materials and Preparation

The materials needed to implement this investigation are listed in Table 22.1 (p. 474). The items can be purchased from a science supply company such as Carolina, Flinn Scientific, PASCO, Vernier, or Ward's Science. We recommend the wind turbine kits from Vernier. You can purchase the KidWind Advanced Wind Experiment Kit (KW-AWXC) or just the KidWind Basic Turbine Building Parts Kit (KW-BTPART). The Advanced Experiment Kit Classroom Pack includes three turbines, extra hubs, and blade consumables for approximately 24 students. The Basic Turbine Building Parts Kit includes a hub, a wind turbine generator, and 25 dowels. You can purchase one kit for each group and then build the turbine base for each group using PVC pipe. Figure 22.1 shows a station built from PVC pipe from two different angles. Instructions for building the PVC stand can be found at *www1.eere.energy.gov/education/pdfs/wind_basicpvcwindturbine.pdf*.

TABLE 22.1

Materials list for Lab 22

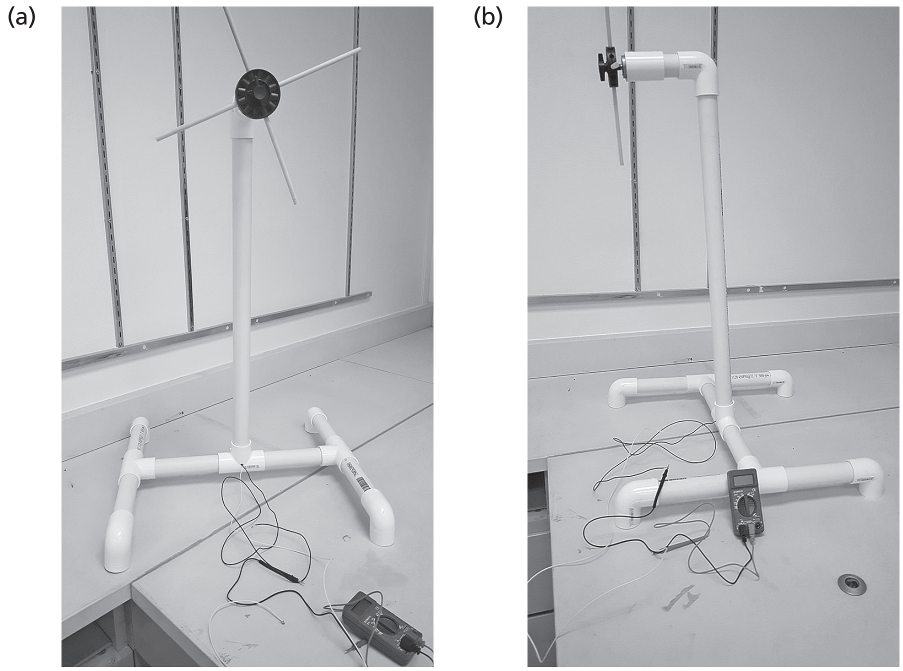
Item	Quantity
Safety glasses or goggles	1 per student
Wind turbine kit with adjustable blades	1 per group
Fan to generate wind	2–4 per class
Multimeter or galvanometer	1 per group
Electric wire	As needed
Lightbulbs (small)	3 per group
Ruler	1 per group
Protractor	1 per group
Investigation Proposal C (optional)	3 per group
Whiteboard, 2' × 3'*	1 per group
Lab Handout	1 per student
Peer-review guide and teacher scoring rubric	1 per student
Checkout Questions	1 per student

* As an alternative, students can use computer and presentation software such as Microsoft PowerPoint or Apple Keynote to create their arguments.

Be sure to use a set routine for distributing and collecting the materials during the lab investigation. One option is to set up the materials for each group at each group's lab station before class begins. This option works well when there is a dedicated section of the classroom for lab work and the materials are large and difficult to move (such as a dynamics track). A second option is to have all the materials on a table or cart at a central location. You can then assign a member of each group to be the "materials manager." This individual is responsible for collecting all the materials his or her group needs from the table or cart during class and for returning all the materials at the end of the class. This option works well when the materials are small and easy to move (such as stopwatches, metersticks, or hanging masses). It also makes it easy to inventory the materials at the end of the class before students leave for the day.

FIGURE 22.1

Wind turbine setup: (a) front view and (b) side view



Safety Precautions

Remind students to follow all normal lab safety rules. In addition, tell students to take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Handle blades with care. They can puncture skin.
3. Electric wire may get hot. Use caution when touching exposed parts of wires.
4. Handle lightbulbs with care. They can get hot and burn skin; also, they are fragile and can break easily, causing a sharp hazard that can cut or puncture skin.
5. Keep fingers and toes out of the way of moving objects.
6. Wash hands with soap and water after completing the lab.

Topics for the Explicit and Reflective Discussion

Reflecting on the Use of Core Ideas and Crosscutting Concepts During the Investigation

Teachers should begin the explicit and reflective discussion by asking students to discuss what they know about the core idea they used during the investigation. The following are some important concepts related to the core idea of Energy that students will need to determine how to maximize the amount of electrical energy produced by a wind turbine:

- Energy, linear momentum, and angular momentum are conserved in all systems under all circumstances.
- Conserved quantities are constant in an isolated or a closed system. An open system is one that exchanges any conserved quantity with its surroundings.
- Kinetic energy after an elastic collision is the same as the kinetic energy before the collision in an isolated system.

To help students reflect on what they know about energy, we recommend showing them two or three images using presentation software that help illustrate these important ideas. You can then ask the students the following questions to encourage them to share how they are thinking about these important concepts:

1. What do we see going on in this image?
2. Does anyone have anything else to add?
3. What might be going on that we can't see?
4. What are some things that we are not sure about here?

You can then encourage students to think about how CCs played a role in their investigation. There are at least three CCs that students need to use to determine how to maximize the amount of electrical energy produced by a wind turbine: (a) Systems and System Models; (b) Energy and Matter: Flows, Cycles, and Conservation; and (c) Structure and Function (see Appendix 2 [p. 527] for a brief description of these CCs). To help students reflect on what they know about these CCs, we recommend asking them the following questions:

1. Scientists often need to define the system under study and then make a model during an investigation. Why is developing a model of a system so useful in science?
2. What were the boundaries and components of the system you studied during this investigation? What were the strengths and limitations of the model you developed?
3. Scientists often attempt to track how energy and matter move into, out of, and within systems as part of an investigation. Why is this useful?

4. How did you attempt to track how energy moves within the system you were studying? What did tracking energy allow you to do during your investigation?
5. The way an object is shaped or structured determines many of its properties and how it functions. Why is it useful to think about the relationship between structure and function during an investigation?
6. Why was it useful to examine the structure of a wind turbine when attempting to determine how much electrical energy it produces?

You can then encourage the students to think about how they used all these different concepts to help answer the guiding question and why it is important to use these ideas to help justify their evidence for their final arguments. Be sure to remind your students to explain why they included the evidence in their arguments and make the assumptions underlying their analysis and interpretation of the data explicit in order to provide an adequate justification of their evidence.

Reflecting on Ways to Design Better Investigations

It is important for students to reflect on the strengths and weaknesses of the investigation they designed during the explicit and reflective discussion. Students should therefore be encouraged to discuss ways to eliminate potential flaws, measurement errors, or sources of uncertainty in their investigations. To help students be more reflective about the design of their investigation and what they can do to make their investigations more rigorous in the future, you can ask them the following questions:

1. What were some of the strengths of the way you planned and carried out your investigation? In other words, what made it scientific?
2. What were some of the weaknesses of the way you planned and carried out your investigation? In other words, what made it less scientific?
3. What rules can we make, as a class, to ensure that our next investigation is more scientific?

Reflecting on the Nature of Scientific Knowledge and Scientific Inquiry

This investigation can be used to illustrate two important concepts related to the nature of scientific knowledge and the nature of scientific inquiry: (a) how scientific knowledge changes over time and (b) how the culture of science, societal needs, and current events influence the work of scientists (see Appendix 2 for a brief description of these two concepts). Be sure to review these concepts during and at the end of the explicit and reflective discussion. To help students think about these concepts in relation to what they did during the lab, you can ask them the following questions:

1. Scientific knowledge can and does change over time. Can you tell me why it changes?
2. Can you work with your group to come up some example of how scientific knowledge has changed over time? Be ready to share in a few minutes.
3. People view some types of research as being more important than other types of research because of cultural values and current events. Can you come up with some examples of how cultural values and current events have influenced the work of scientists?
4. Scientists share a set of values, norms, and commitments that shape what counts as knowing, how to represent or communicate information, and how to interact with other scientists. Can you work with your group to come up with a rule that you can use to decide if something is science or not science? Be ready to share in a few minutes.

You can also use presentation software or other techniques to encourage your students to think about these concepts. You can show examples of how our thinking about energy has changed over time and ask students to discuss what they think led to those changes. You can also show examples of research projects that were influenced by cultural values and current events and ask students to think about what was going on at the time and why that research was viewed as being important for the greater good.

Be sure to remind your students that, to be proficient in science, it is important that they understand what counts as scientific knowledge and how that knowledge develops over time.

Hints for Implementing the Lab

- Allowing students to design their own procedures for collecting data gives students an opportunity to try, to fail, and to learn from their mistakes. However, you can scaffold students as they develop their procedure by having them fill out an investigation proposal. These proposals provide a way for you to offer students hints and suggestions without telling them how to do it. You can also check the proposals quickly during a class period. We recommend having students fill out an investigation proposal for each experiment. For this lab we suggest using Investigation Proposal C.
- Learn how to use the wind turbine generator before the lab begins. It is important for you to know how to use the equipment so you can help students when technical issues arise.
- Allow students to become familiar with the wind turbine kit as part of the tool talk before they begin to design their investigation. Giving them 5–10 minutes to examine the equipment will let them see what they can and cannot do with it. This

also gives students a chance to begin thinking about what variables to test and how to control for other variables.

- We recommend setting up two to four "testing stations" throughout your classrooms. Students can then arrange the angle of their turbine blades on the rotor and just place the rotor on the generator to test their design. They can then remove the rotor (the black piece in Figure 22.1) from the generator while they adjust the pitch, thereby allowing another group to collect data. This will reduce the cost of equipment.
- Be sure to allow students to go back and re-collect data at the end of the argumentation session. Students often realize that they made numerous mistakes when they were collecting data as a result of their discussions during the argumentation session. The students, as a result, will want a chance to re-collect data, and the re-collection of data should be encouraged when time allows. This also offers an opportunity to discuss what scientists do when they realize a mistake is made inside the lab.

Connections to Standards

Table 22.2 (p. 480) highlights how the investigation can be used to address specific performance expectations from the *NGSS;* learning objectives from AP Physics 1; learning objectives from AP Physics C: Mechanics, *Common Core State Standards,* in English language arts (*CCSS ELA*); and *Common Core State Standards,* Mathematics (*CCSS Mathematics*).

TABLE 22.2

Lab 22 alignment with standards

***NGSS* performance expectations**	• HS-PS3-3: Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.
AP Physics 1 learning objectives	• 5.D.1.4: The student is able to design an experimental test of an application of the principle of the conservation of linear momentum, predict an outcome of the experiment using the principle, analyze data generated by that experiment whose uncertainties are expressed numerically, and evaluate the match between the prediction and the outcome.
AP Physics C: Mechanics learning objectives	• I.C.3.a(2): Describe and identify situations in which mechanical energy is converted to other forms of energy. • I.C.3.b(1): Identify situations in which mechanical energy is or is not conserved.
Literacy connections (*CCSS ELA*)	• *Reading:* Key ideas and details, craft and structure, integration of knowledge and ideas • *Writing:* Text types and purposes, production and distribution of writing, research to build and present knowledge, range of writing • *Speaking and listening:* Comprehension and collaboration, presentation of knowledge and ideas
Mathematics connections (*CCSS Mathematics*)	• *Mathematical practices:* Make sense of problems and persevere in solving them, reason abstractly and quantitatively, construct viable arguments and critique the reasoning of others, model with mathematics, use appropriate tools strategically, attend to precision, look for and make use of structure, look for and express regularity in repeated reasoning • *Number and quantity:* Reason quantitatively and use units to solve problems, represent and model with vector quantities, perform operations on vectors • *Algebra:* Interpret the structure of expressions, create equations that describe numbers or relationships, understand solving equations as a process of reasoning and explain the reasoning, solve equations and inequalities in one variable, represent and solve equations and inequalities graphically • *Functions:* Understand the concept of a function and use function notation, interpret functions that arise in applications in terms of the context, analyze functions using different representations, build a function that models a relationship between two quantities, construct and compare linear and exponential models and solve problems, interpret expressions for functions in terms of the situation they model • *Statistics and probability:* Summarize, represent, and interpret data on two categorical and quantitative variables; interpret linear models; understand and evaluate random processes underlying statistical experiments; make inferences and justify conclusions from sample surveys, experiments, and observational studies

Lab Handout

Lab 22. Conservation of Energy and Wind Turbines: How Can We Maximize the Amount of Electrical Energy That Will Be Generated by a Wind Turbine Based on the Design of Its Blades?

Introduction

The United States relies heavily on fossil fuels, such as oil, coal, and natural gas, for energy. Americans burn fossil fuels to power their cars, to heat and light their homes, and to run their consumer electronics and household appliances. Unfortunately, when the supply of fossil fuels declines, it can lead to an energy crisis. In 1973, for example, the Organization of the Petroleum Exporting Companies (OPEC) declared an oil embargo and drastically reduced the amount of oil they sent to the United States. This six-month embargo caused widespread gasoline shortages and significant price increases. A second oil crisis in the United States occurred in 1979 as a result of a decrease in the output of oil from the Middle East along with price increases. This decrease in output resulted in gasoline shortages and long lines at gasoline stations throughout the United States (see Figure L22.1).These events led to a political push for policies that would make America more energy independent. A country that is energy independent does not need to import oil or other forms of energy from other countries to meet the energy demands of its citizens.

FIGURE L22.1

A long line at a gas station in Maryland as a result of the 1979 oil crisis

More recently, evidence that the burning of fossil fuels contributes to climate change has exacerbated the need to develop new energy sources. To combat the effects of climate change, scientists have been working on ways to harness and use renewable energy sources. Renewable energy sources are forms of energy that are continuously replenished. Solar, tidal, and geothermal energy are examples of renewable energy sources. Furthermore, all renewable energy sources are clean, which means they do not contribute to climate change. These sources of energy, however, are often difficult to access without the development of new technologies.

One of the more promising renewable energy sources is wind. Wind is just the movement of a large number of air particles from one area to another. In the United States, wind energy is a very attractive option because the Great Plains states of Texas, Oklahoma, Kansas, Nebraska, and the Dakotas have vast open spaces where wind blows for extended periods of time. Wind energy takes advantage of the law of conservation of energy to convert the kinetic energy of air particles (gases such nitrogen [N_2], oxygen [O_2], water vapor, and others) into electrical energy. To achieve this conversion, several huge wind turbines are built to create a wind farm (see Figure L22.2). When air particles collide with the blades on the turbine, they transfer some momentum to the blades. This momentum transfer causes the turbine to spin, resulting in an increase in the kinetic energy of the turbine blades. The turbine then turns a generator, producing an electric current from a transfer of kinetic energy to electric energy. Wires carry the current to other locations, for use in homes and businesses.

FIGURE L22.2

A wind farm

When designing a wind turbine, scientists and engineers must account for a variety of factors related to how and where wind blows. As mentioned earlier, wind farms are best placed in the Great Plains, yet only a small percentage of people live in this geographic location, so scientists and engineers must also think about how to move the energy generated to more populous areas. Another factor is the height of the turbine. Wind tends to blow faster at higher altitudes, meaning the height of the turbine affects the amount of energy produced. Other potential factors that may influence the amount of electrical energy produced include the angle of the blades relative to the wind, the number of blades on the turbine, and the shape and mass of the turbine blades.

Your Task

Use what you know about the conservation of energy, systems, models, and structure and function to test the effect of changes to the design of wind turbine blades on the amount of electrical energy produced by the wind turbine. Your goal is to determine how the angle, number, and shape of the blades that are attached to the wind turbine affect the amount of electrical energy that the wind turbine is able to produce.

The guiding question of this investigation is, ***How can we maximize the amount of electrical energy that will be generated by a wind turbine based on the design of its blades?***

Materials

You may use any of the following materials during your investigation:

- Safety glasses or goggles (required)
- Wind turbine kit with adjustable blades
- Fan to generate wind
- Multimeter or galvanometer
- Electric wires
- Lightbulbs
- Ruler
- Protractor

Safety Precautions

Follow all normal lab safety rules. In addition, take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Handle blades with care. They can puncture skin.
3. Electric wire may get hot. Use caution when touching exposed parts of wires.
4. Handle lightbulbs with care. They can get hot and burn skin; also, they are fragile and can break easily, causing a sharp hazard that can cut or puncture skin.
5. Keep fingers and toes out of the way of moving objects.
6. Wash hands with soap and water after completing the lab.

Investigation Proposal Required? ☐ Yes ☐ No

Getting Started

You will need to design and carry out at least three different experiments to determine how to maximize the amount of electrical energy that is generated by a wind turbine based on the design of its blades. You will need to conduct three different experiments because you will need to be able to answer the following questions before you can develop an answer to the guiding question for this lab:

1. How does changing the number of blades affect the energy output of the turbine?
2. How does changing the shape of the blades affect the energy output of the turbine?
3. How does changing the angle of the blades affect the energy output of the turbine?

It will be important for you to determine what type of data you need to collect, how you will collect it, and how you will analyze it for each experiment, because each experiment is slightly different.

To determine *what type of data you need to collect,* think about the following questions:

- What are the boundaries and components of the system you are studying?
- How do the components of the system interact with each other?
- How can you describe the components of the system quantitatively?
- How could you keep track of changes in this system quantitatively?
- How might the structure of a wind turbine blade relate to its function?
- How might changes to the structure of a wind turbine blade affect how it functions?
- Is it useful to track how energy flows into, out of, or within this system?
- What will be the independent variable and the dependent variable for each experiment?

To determine *how you will collect the data,* think about the following questions:

- How will you vary the independent variable during each experiment?
- What will you do to hold the other variables constant during each experiment?
- When will you need to take measurements or observations during each experiment?
- What scale or scales should you use when you take your measurements?

To determine *how you will analyze the data,* think about the following questions:

- What types of calculations will you need to make?
- What types of comparisons will you need to make?
- How could you use mathematics to determine if there is a difference between the groups?
- What type of table or graph could you create to help make sense of your data?

Connections to the Nature of Scientific Knowledge and Scientific Inquiry

As you work through your investigation, you may want to consider

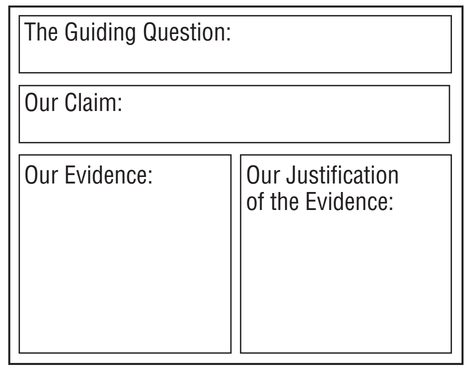
- how scientific knowledge changes over time, and
- how the culture of science, societal needs, and current events influence the work of scientists.

Initial Argument

Once your group has finished collecting and analyzing your data, your group will need to develop an initial argument. Your initial argument needs to include a claim, evidence to support your claim, and a justification of the evidence. The *claim* is your group's answer to the guiding question. The *evidence* is an analysis and interpretation of your data. Finally, the *justification* of the evidence is why your group thinks the evidence matters. The justification of the evidence is important because scientists can use different kinds of evidence to support their claims. Your group will create your initial argument on a whiteboard. Your whiteboard should include all the information shown in Figure L22.3.

FIGURE L22.3

Argument presentation on a whiteboard



Argumentation Session

The argumentation session allows all of the groups to share their arguments. One or two members of each group will stay at the lab station to share that group's argument, while the other members of the group go to the other lab stations to listen to and critique the other arguments. This is similar to what scientists do when they propose, support, evaluate, and refine new ideas during a poster session at a conference. If you are presenting your group's argument, your goal is to share your ideas and answer questions. You should also keep a record of the critiques and suggestions made by your classmates so you can use this feedback to make your initial argument stronger. You can keep track of specific critiques and suggestions for improvement that your classmates mention in the space below.

Critiques about our initial argument and suggestions for improvement:

If you are critiquing your classmates' arguments, your goal is to look for mistakes in their arguments and offer suggestions for improvement so these mistakes can be fixed. You should look for ways to make your initial argument stronger by looking for things that the other groups did well. You can keep track of interesting ideas that you see and hear during the argumentation in the space below. You can also use this space to keep track of any questions that you will need to discuss with your team.

Interesting ideas from other groups or questions to take back to my group:

Once the argumentation session is complete, you will have a chance to meet with your group and revise your initial argument. Your group might need to gather more data or design a way to test one or more alternative claims as part of this process. Remember, your goal at this stage of the investigation is to develop the best argument possible.

Report

Once you have completed your research, you will need to prepare an *investigation report* that consists of three sections. Each section should provide an answer to the following questions:

1. What question were you trying to answer and why?
2. What did you do to answer your question and why?
3. What is your argument?

Your report should answer these questions in two pages or less. This report must be typed, and any diagrams, figures, or tables should be embedded into the document. Be sure to write in a persuasive style; you are trying to convince others that your claim is acceptable or valid!

Checkout Questions

Lab 22. Conservation of Energy and Wind Turbines: How Can We Maximize the Amount of Electrical Energy That Will Be Generated by a Wind Turbine Based on the Design of Its Blades?

1. The electrical energy produced by a wind turbine originates as solar energy. Describe the processes that transfer solar energy from the Sun into electrical energy in the wires produced by the turbine.

2. Using concepts of (1) conservation of momentum, (2) conservation of energy, (3) the definition of momentum as a vector quantity, and (4) the definition of energy as a scalar quantity, explain why there is a maximum value for the energy output for one of the variables you tested.

3. People view some research as being more important than other research because of current events or what is important in society.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about wind turbines.

4. Scientific knowledge, once it has been proven true, does not change.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about wind turbines.

5. How something is structured can affect that object's function.
   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about wind turbines.

6. Scientists often need to track how matter moves into and within a system. Explain why this is important, using an example from your investigation about wind turbines.

7. Scientists often need to define a system under study and then create a model during an investigation. Explain why models of systems are useful in science, using an example from your investigation about wind turbines.

Application Lab

Teacher Notes

Lab 23. Power: Which Toy Car Has the Engine With the Greatest Horsepower?

Purpose

The purpose of this lab is for students to *apply* what they know about the disciplinary core idea (DCI) of Energy from the *NGSS* to measure the horsepower of a toy car. This lab also gives students an opportunity to learn about the crosscutting concepts (CCs) of (a) Systems and System Models and (b) Energy and Matter: Flows, Cycles, and Conservation from the *NGSS.* In addition, this lab can be used to help students understand four big ideas from AP Physics: (a) objects and systems have properties such as mass and charge, (b) the interactions of an object with other objects can be described by forces, (c) interactions between systems can result in changes in those systems, and (d) changes that occur as result of interactions are constrained by conservation laws. As part of the explicit and reflective discussion, students will also learn about (a) the difference between observations and inferences in science and (b) the role of imagination and creativity in science.

Underlying Physics Concepts

Power is defined as the rate at which work is done or the rate at which energy is produced or used. The work done on an object is the magnitude of a constant force applied to the object times the displacement of that object in the direction of the force. We can mathematically represent power and work through Equations 23.1 and 23.2, respectively. In these equations, P is power, W is work, t is time, $\mathbf{F}$ is force, and $\mathbf{d}$ is displacement. Also, notice that a capital P is used for power, because lowercase $\mathbf{p}$ is used for momentum. In SI units, power is measured in watts (W), work is measured in joules (J), time is measured in seconds (s), force is measured in newtons (N), and displacement is measured in meters (m).

(Equation 23.1) $P = W/t$

(Equation 23.2) $W = \mathbf{Fd}$

We also know that force is the mass of an object times its acceleration, which gives us Equation 23.3, where m is mass and $\mathbf{a}$ is acceleration. In SI units, mass is measured in kilograms (kg) and acceleration is measured in meters per second squared (m/s^2).

(Equation 23.3) $W = m\mathbf{ad}$

We can then combine Equations 23.1 and 23.3 to get Equation 23.4.

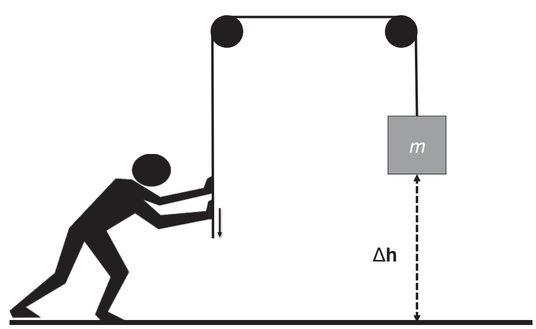
(Equation 23.4) $P = m\mathbf{a}\mathbf{d}/t$

What is important to note about all of these equations is the relationship between work and power. Work causes a transformation in the amount or type of energy that an object has. For example, when an object falls toward the ground, work is done by gravity to transfer the energy of the object from potential energy to kinetic energy. Yet, the total energy of the object remains unchanged. At the same time, we can do work on a stationary object to give it kinetic energy by pushing it or pulling it. In this case, work changes the energy of an object. Power is the change in energy of an object divided by the time it takes to induce that change in energy. Thus, power is a measure of the rate at which work is done on an object. Put another way, power is a measure of the rate of change of the energy of an object due to work done on that object.

Finally, if the work done to an object is to change the potential energy of the object, then the power of the object doing the work can be calculated using the change in potential energy. Figure 23.1 shows a person lifting a box of mass m with a pulley system. The person does work on the box by pulling it up a displacement of $\Delta\mathbf{h}$. To calculate the power of the person when pulling the box, we need to calculate the change in energy of the box and divide that by the total time it took to lift the box. Because the person is doing work to change the potential energy of the box, the work done is equal to the change in gravitational potential energy when the box is lifted $\Delta\mathbf{h}$. Mathematically, the power output of the person is expressed in Equation 23.5, where $\mathbf{g}$ is the acceleration due to gravity and is a constant equal to 9.8 m/s^2.

FIGURE 23.1

Lifting an object

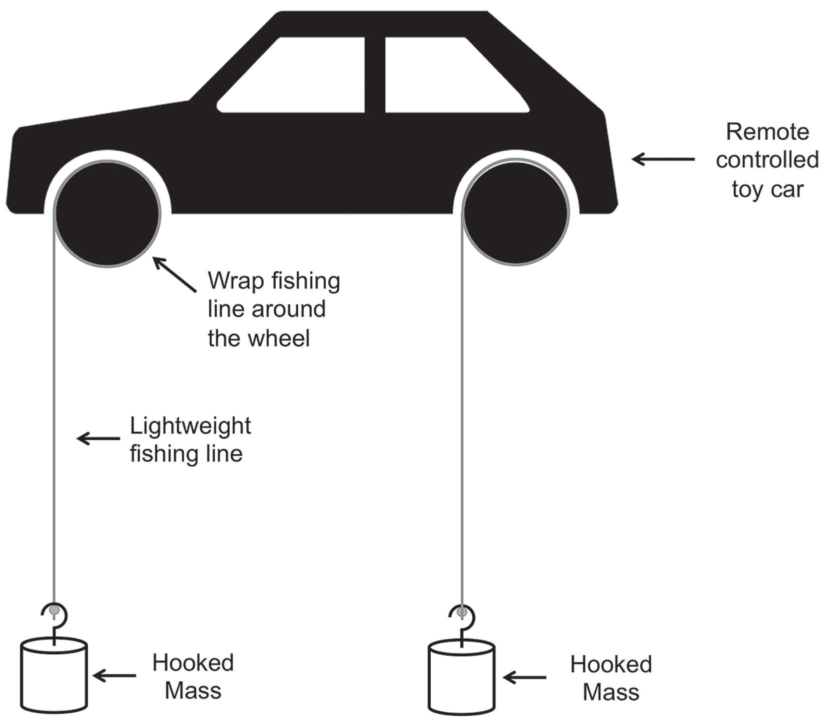


(Equation 23.5) $P = m\mathbf{g}\Delta\mathbf{h}/t$

The easiest way to measure the horsepower of a toy car during this investigation is to suspend it in the air and attach a mass to each wheel. Then, measure the time it takes for each wheel to lift the mass 1 meter off the ground. The power of the engine is the total amount of potential energy added to the system divided by the amount of time during which the energy was added. In other words, add the potential energy for each mass while the wheels spin and divide the total potential energy by the time it takes to lift the masses. Figure 23.2 shows how this method can be used to measure the horsepower of a toy car engine. Notice that each wheel has a mass attached to it.

FIGURE 23.2

A possible way to measure the horsepower of a toy car.



A second way to measure the horsepower of a toy car during this investigation is to determine the amount of time it takes the car to pull a mass behind it. The students can then calculate the sum of the forces on the mass, and assuming they calculate the coefficient of friction between the mass and the floor, they can then calculate the force applied by the car's engine to pull the mass. Because the car pulled the mass a specific distance in a specific amount of time, we know the power of the car's engine is the force applied by the car times the displacement of the mass divided by the time it takes the car to pull the mass. Mathematically, this is expressed in Equation 23.6.

(Equation 23.6) $P = \mathbf{F}_{car}\mathbf{d}_{mass}/t$

A third possible way to measure the horsepower of a car is to find the amount of time it takes the car to reach its maximum velocity when starting from rest. Students can then use equations of motion to calculate the average acceleration of the car. The average force applied by the engine is the average acceleration of the car times the mass of the car. In this case, power can be calculated via Equation 23.7.

$$\text{(Equation 23.7)} \quad P = \mathbf{m}_{car}\mathbf{a}_{car}\mathbf{d}/t$$

The first method has the least amount of error inherent in the design. It is fine if students use the other two methods, because it provides an opportunity for students to think about experimental design and error.

Timeline

The instructional time needed to complete this lab investigation is 200–280 minutes. Appendix 3 (p. 531) provides options for implementing this lab investigation over several class periods. Option E (280 minutes) should be used if students are unfamiliar with scientific writing, because this option provides extra instructional time for scaffolding the writing process. You can scaffold the writing process by modeling, providing examples, and providing hints as students write each section of the report. Option E can also be used if you are introducing students to the video analysis programs. Option F (200 minutes) should be used if students are familiar with scientific writing and have developed the skills needed to write an investigation report on their own. In option F, students complete stage 6 (writing the investigation report) and stage 8 (revising the investigation report) as homework.

Materials and Preparation

The materials needed to implement this investigation are listed in Table 23.1. The items can be purchased from a science supply company such as Carolina, Flinn Scientific, PASCO, Vernier, or Ward's Science. The remote control or toy car can be purchased from Wal-Mart or online at Amazon.com. Video analysis software can be purchased from Vernier (Logger *Pro*) or PASCO (SPARKvue or Capstone). These companies also have apps that can be used on Apple- or Android-based tablets and cell phones. We recommend consulting with your school's information technology coordinator to determine the best option for your students.

TABLE 23.1

Materials list for Lab 23

Item	Quantity
Consumables	
Tape	1 roll per group
String or fishing line	1 roll per group
Equipment and other materials	
Safety glasses or goggles	1 per student
Remote control car type or brand A	2 per class

continued

Table 23.1 (*continued*)

Remote control car type or brand B	2 per class
Remote control car type or brand C	2 per class
Remote control car type or brand D	2 per class
Hanging mass set	1 per group
Electronic or triple beam balance	1 per group
Stopwatches	2 per group
Ruler	1 per student
Metersticks	4 per group
Investigation Proposal A (optional)	1 per group
Whiteboard, 2' × 3'*	1 per group
Lab Handout	1 per student
Peer-review guide and teacher scoring rubric	1 per student
Checkout Questions	1 per student
Equipment for video analysis (optional)	
Video camera	1 per group
Computer or tablet with video analysis software	1 per group

* As an alternative, students can use computer and presentation software such as Microsoft PowerPoint or Apple Keynote to create their arguments.

Be sure to use a set routine for distributing and collecting the materials during the lab investigation. One option is to set up the materials for each group at each group's lab station before class begins. This option works well when there is a dedicated section of the classroom for lab work and the materials are large and difficult to move (such as a dynamics track). A second option is to have all the materials on a table or cart at a central location. You can then assign a member of each group to be the "materials manager." This individual is responsible for collecting all the materials his or her group needs from the table or cart during class and for returning all the materials at the end of the class. This option works well when the materials are small and easy to move (such as stopwatches, metersticks, or hanging masses). It also makes it easy to inventory the materials at the end of the class before students leave for the day.

Safety Precautions

Remind students to follow all normal lab safety rules. In addition, tell students to take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Wash hands with soap and water after completing the lab.

Topics for the Explicit and Reflective Discussion

Reflecting on the Use of Core Ideas and Crosscutting Concepts During the Investigation

Teachers should begin the explicit and reflective discussion by asking students to discuss what they know about the core idea they used during the investigation. The following are some important concepts related to the core idea of Energy that students will need to determine the horsepower of a toy car:

- The change in an object's kinetic energy depends on the force exerted on the object and on the displacement of the object during the time interval that the force is exerted.
- Mechanical energy, which is the sum of kinetic and potential energy, is transferred into or out of a system when an external force is exerted on a system such that a component of the force is parallel to its displacement. The process through which mechanical energy is transferred into or out of a system is called *work.*
- If the force is constant during a given displacement, then the work done is the product of the displacement and the component of the force parallel or antiparallel to the displacement.

To help students reflect on what they know about energy, we recommend showing them two or three images using presentation software that help illustrate these important ideas. You can then ask the students the following questions to encourage them to share how they are thinking about these important concepts:

1. What do we see going on in this image?
2. Does anyone have anything else to add?
3. What might be going on that we can't see?
4. What are some things that we are not sure about here?

You can then encourage students to think about how CCs played a role in their investigation. There are at least two CCs that students need to use to determine the horsepower of a toy car: (a) Systems and System Models and (b) Energy and Matter: Flows, Cycles, and Conservation (see Appendix 2 [p. 527] for a brief description of these CCs). To help students reflect on what they know about these CCs, we recommend asking them the following questions:

1. Scientists often need to define the system under study and then make a model during an investigation. Why is developing a model of system so useful in science?
2. What were the boundaries and components of the system you studied during this investigation?
3. Scientists often attempt to track how energy and matter move into, out of, and within systems as part of an investigation. Why is this useful?
4. How did you attempt to track how energy moves within the system you were studying? What did tracking energy allow you to do during your investigation?

You can then encourage the students to think about how they used all these different concepts to help answer the guiding question and why it is important to use these ideas to help justify their evidence for their final arguments. Be sure to remind your students to explain why they included the evidence in their arguments and make the assumptions underlying their analysis and interpretation of the data explicit in order to provide an adequate justification of their evidence.

Reflecting on Ways to Design Better Investigations

It is important for students to reflect on the strengths and weaknesses of the investigation they designed during the explicit and reflective discussion. Students should therefore be encouraged to discuss ways to eliminate potential flaws, measurement errors, or sources of uncertainty in their investigations. To help students be more reflective about the design of their investigation and what they can do to make their investigations more rigorous in the future, you can ask them the following questions:

1. What were some of the strengths of the way you planned and carried out your investigation? In other words, what made it scientific?
2. What were some of the weaknesses of the way you planned and carried out your investigation? In other words, what made it less scientific?
3. What rules can we make, as a class, to ensure that our next investigation is more scientific?

Reflecting on the Nature of Scientific Knowledge and Scientific Inquiry

This investigation can be used to illustrate two important concepts related to the nature of scientific knowledge and the nature of scientific inquiry: (a) the difference between observations and inferences in science and (b) the role of imagination and creativity in science (see Appendix 2 for a brief description of these two concepts). Be sure to review these concepts during and at the end of the explicit and reflective discussion. To help students think about these concepts in relation to what they did during the lab, you can ask them the following questions:

1. You had to make observations and inferences during your investigation. Can you give me some examples of these observations and inferences?
2. Can you work with your group to come up with a rule that you can use to decide if a piece of information is an observation or an inference? Be ready to share in a few minutes.
3. Some people think that there is no room for imagination or creativity in science. What do you think?
4. Can you work with your group to come up with different ways that you needed to use your imagination or be creative during this investigation? Be ready to share in a few minutes.

You can also use presentation software or other techniques to encourage your students to think about these concepts. You can show examples of information from the investigation that are either observations or inferences and ask students to classify each example and explain their thinking. You can also show students an image of the following quote by E. O. Wilson from *Letters to a Young Scientist* (2013) and ask them what they think he meant by it:

> The ideal scientist thinks like a poet and only later works like a bookkeeper. Keep in mind that innovators in both literature and science are basically dreamers and storytellers. In the early stages of the creation of both literature and science, everything in the mind is a story. There is an imagined ending, and usually an imagined beginning, and a selection of bits and pieces that might fit in between. In works of literature and science alike, any part can be changed, causing a ripple among the other parts, some of which are discarded and new ones added. (p. 74)

Be sure to remind your students that, to be proficient in science, it is important that they understand what counts as scientific knowledge and how that knowledge develops over time.

Hints for Implementing the Lab

- Allowing students to design their own procedures for collecting data gives students an opportunity to try, to fail, and to learn from their mistakes. However, you can scaffold students as they develop their procedure by having them fill out an investigation proposal. These proposals provide a way for you to offer students hints and suggestions without telling them how to do it. You can also check the proposals quickly during a class period. For this lab we suggest using Investigation Proposal A.
- We recommend that you try each potential method (setup) on your own before students collect data. This will allow you to become familiar with the range of

masses that can be added to the car. Too much mass added to the car can cause the engine to burn out.

- Allow the students to become familiar with the equipment and materials as part of the tool talk before they begin to design their investigation. Giving them 5–10 minutes to examine the available equipment and materials will let them see what they can and cannot do with them. This also gives students a chance to begin thinking about what variables to test and how to control for other variables.
- Do not give students masses that are large enough to lead to the engine burning out.
- We recommend using lightweight but high-strength fishing wire for this investigation. Lightweight wire will add negligible mass to each wheel but will be strong enough to support the tension.
- Students can suspend the car on two metersticks taped to a table with the ends hanging off the table, or they can suspend the car on a ring stand. If students do use metersticks taped to the table, make sure the metersticks are secure and able to support the mass of the toy car.
- We recommend using remote control toy cars with large tires (such as the one shown in Figure 23.2 [p. 494]) for this lab. You only need to have four different types or brands of cars for the students to test. That way, you can purchase two cars of each type or brand (2 cars × 4 different types or brands = total of 8 cars). Each group can develop their method for measuring horsepower using one car and then test the other three types or brands of toy car. This will allow each group to test the same four types or brands of cars without having to purchase four different cars for each group to test.
- Be sure to allow students to go back and re-collect data at the end of the argumentation session. Students often realize that they made numerous mistakes when they were collecting data as a result of their discussions during the argumentation session. The students, as a result, will want a chance to re-collect data, and the re-collection of data should be encouraged when time allows. This also offers an opportunity to discuss what scientists do when they realize a mistake is made inside the lab.

If students use video analysis

- We suggest allowing students to familiarize themselves with the video analysis software before they finalize the procedure for the investigation, especially if they have not used such software previously. This gives students an opportunity to learn how to work with the software and to improve the quality of the video they take.
- Remind students to hold the video camera as still as possible. Any movement of the camera will introduce error into their analysis. If using actual camcorders,

we recommend using a tripod to hold the camera steady. If students are using a camera on a cell phone or tablet, we recommend using a table to help steady the camera.

- Remind students to place a meterstick in the same field of view as the motion they are capturing with the video camera. Also, the meterstick should be approximately the same distance from the camera as the motion. Most video analysis software requires the user to define a scale in the video (this allows the software to establish distances and, subsequently, other variables dependent on distance and displacement).

Connections to Standards

Table 23.2 highlights how the investigation can be used to address learning objectives from AP Physics 1; learning objectives from AP Physics C: Mechanics, *Common Core State Standards,* in English language arts (*CCSS ELA*); and *Common Core State Standards,* Mathematics (*CCSS Mathematics*).

TABLE 23.2

Lab 23 alignment with standards

***NGSS* performance expectations**	• None
AP Physics 1 learning objectives	• 4.C.2.2: The student is able to apply the concepts of conservation of energy and the work-energy theorem to determine qualitatively and/or quantitatively that work done on a two-object system in linear motion will change the kinetic energy of the center of mass of the system, the potential energy of the systems, and/or the internal energy of the system. • 5.B.1.2: The student is able to translate between a representation of a single object, which can only have kinetic energy, and a system that includes the object, which may have both kinetic and potential energies. • 5.B.5.1: The student is able to design an experiment and analyze data to examine how a force exerted on an object or system does work on the object or system as it moves through a distance. • 5.B.5.4: The student is able to make claims about the interaction between a system and its environment in which the environment exerts a force on the system, thus doing work on the system and changing the energy of the system (kinetic energy plus potential energy). • 5.B.5.5: The student is able to predict and calculate the energy transfer to (i.e., the work done on) an object or system from information about a force exerted on the object or system through a distance.

continued

Table 23.2 (*continued*)

AP Physics C: Mechanics learning objectives	• I.C.1.a: Students should understand the definition of work, including when it is positive, negative, or zero. • I.C.1.a(1): Calculate the work done by a specified constant force on an object that undergoes a specified displacement. • I.C.2.b(2): Calculate a potential energy function associated with a specified one-dimensional force **F**(**x**). • I.C.3.a(1): State and apply the relation between the work performed on an object by nonconservative forces and the change in an object's mechanical energy. • I.C.3.b(1): Identify situations in which mechanical energy is or is not conserved. • I.C.4.b: Calculate the work performed by a force that supplies constant power, or the average power supplied by a force that performs a specified amount of work.
Literacy connections (*CCSS ELA*)	• *Reading*: Key ideas and details, craft and structure, integration of knowledge and ideas • *Writing:* Text types and purposes, production and distribution of writing, research to build and present knowledge, range of writing • *Speaking and listening:* Comprehension and collaboration, presentation of knowledge and ideas
Mathematics connections (*CCSS Mathematics*)	• *Mathematical practices:* Reason abstractly and quantitatively, construct viable arguments and critique the reasoning of others, use appropriate tools strategically, attend to precision • *Number and quantity:* Reason quantitatively and use units to solve problems, represent and model with vector quantities, perform operations on vectors • *Algebra:* Interpret the structure of expressions, understand solving equations as a process of reasoning and explain the reasoning, solve equations and inequalities in one variable, represent and solve equations and inequalities graphically • *Functions:* Understand the concept of a function and use function notation, interpret functions that arise in applications in terms of the context, analyze functions using different representations, interpret expressions for functions in terms of the situation they model • *Statistics and probability:* Summarize, represent, and interpret data on two categorical and quantitative variables; understand and evaluate random processes underlying statistical experiments; make inferences and justify conclusions from sample surveys, experiments, and observational studies

Reference

Wilson, E. O. 2013. *Letters to a young scientist.* New York: Liveright Publishing.

Lab Handout

Lab 23. Power: Which Toy Car Has the Engine With the Greatest Horsepower?

Introduction

With the onset of the Industrial Revolution, many people wanted a way to compare the capabilities of new machines with existing ways of doing things. For example, when James Watt started building and selling steam engines in the late 18th century, one of his customers asked Watt to compare the power of the engine with the power of a horse. The customer, in other words, wanted to know if the new steam engine could do the same things a horse could do. Watt used the term *horsepower* as a convenient way of comparing the power of his steam engine with the power of a horse. Figure L23.1 shows a painting by Carl Rakeman of a race in 1830 between a horse-drawn cart and the first steam locomotive built in the United States, which was called Tom Thumb. This race was an important event leading to the rise of the railroad industry in America because it demonstrated that a steam-powered locomotive could outperform a horse. Since then, *horsepower* has been given a formal definition as a unit of measure, with 1 horsepower (hp) equal to 746 watts (W).

FIGURE L23.1

Painting by Carl Rakeman of the Tom Thumb steam-powered locomotive racing a horse

Note: A full-color, high-resolution version of this image is available on the book's Extras page at *www.nsta.org/adi-physics1*.

Although most countries use the watt or kilowatt as the standard unit of power, in the United States horsepower is still quite common. Most devices that are powered by an engine or motor are advertised based upon their horsepower; these include household devices such as blenders, lawnmowers, and electric garage door openers. The most common use for horsepower is to describe the power of a car engine. Most everyday cars have an engine of approximately 150 hp, but the fastest sports cars can have engines that are up to 600 hp. And race cars can have engines that are over 800 hp.

An independent group must verify the advertised horsepower of a new engine before a company can sell that engine or a vehicle with that engine in it. An independent group can use several different methods to measure the horsepower of an engine that they did not build; these methods are based on the conservation of energy and the relationship between work and power. The two most common methods are (1) to measure how long it takes the engine to lift or pull a mass a given distance and (2) to measure the amount of time it takes the car to reach its maximum velocity when starting from rest and then use the work-energy theorem to determine the maximum horsepower of the engine. In this investigation, you will have an opportunity to develop your own method for measuring the horsepower of a toy car's engine using the work-energy theorem.

Your Task

Use what you know about the conservation of energy, the relationship between work and power, systems and system models, and the importance of tracking the flow of energy in a system to develop a method for measuring the horsepower of a toy car engine. You will then test the engines of several different toy cars using your method to determine which one has the greatest horsepower.

The guiding question of this investigation is, ***Which toy car has the engine with the greatest horsepower?***

Materials

You may use any of the following materials during your investigation:

Consumables
- Tape
- String or fishing line

Equipment
- Safety glasses or goggles (required)
- 4 Different types or brands of remote control cars
- Hanging mass set
- Electronic or triple beam balance
- Stopwatches
- Ruler
- Metersticks

If you have access to the following equipment, you may also consider using a video camera and a computer or tablet with video analysis software.

Safety Precautions

Follow all normal lab safety rules. In addition, take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on-activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Wash hands with soap and water after completing the lab.

Investigation Proposal Required? ☐ Yes ☐ No

Getting Started

To answer the guiding question, you will need to create a method that you can use to determine the horsepower of the engine found inside a toy car. This means you will need to determine the maximum power that the engine is able to produce. *Power* is defined as the rate at which work is done on an object. The equation for power is $P = W/t$, where W is work and t is time. The term *work* is used to describe any situation when a force acts on an object over a displacement of that object. For a force to qualify as having done work on an object, there must be a displacement and the force must be either parallel to the displacement (e.g., a force to the right with a displacement to the right) or antiparallel to the displacement (e.g., a force to the right with a displacement to the left). The equation for work is $W = \mathbf{Fd}$, where $\mathbf{F}$ is force and $\mathbf{d}$ is displacement. Finally, and perhaps most important in terms of your goal for this investigation, energy cannot be created or destroyed—it just changes form as objects move or as it transfers from one object to another one. You will need to use these fundamental ideas as the foundation for the method you will develop, but there may also be other ideas that you need to use.

To determine *what type of data you need to collect,* think about the following questions:

- What are the boundaries and components of the system under study?
- How can you describe the components of the system quantitatively?
- How could you keep track of changes in this system quantitatively?
- Is it useful to track how energy flows into, out of, or within this system?
- How might the structure of the toy car affect its function?
- How might the structure of the test of horsepower affect its function?

To determine *how you will collect the data*, think about the following questions:

- What types of equipment will you need to use and how will you use it?
- How will you track the flow of energy into, out of, and within the system under study?
- What scale or scales should you use when you take your measurements?
- How will you make sure that your data are of high quality (i.e., how will you reduce error)?
- How will you keep track of the data you collect?

To determine *how you will analyze the data,* think about the following questions:

- What type of calculations will you need to make?
- What types of comparisons will you need to make?

- What type of table or graph could you create to help make sense of your data?

Connections to the Nature of Scientific Knowledge and Scientific Inquiry

As you work through your investigation, you may want to consider

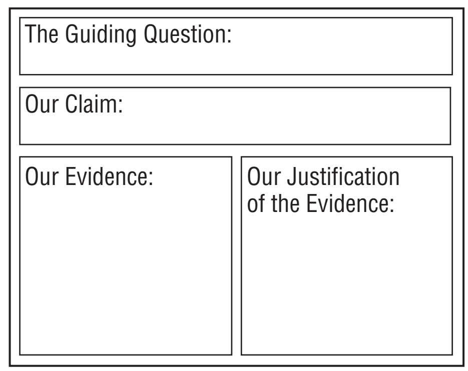
- the difference between observations and inferences in science, and
- the role of imagination and creativity in science.

Initial Argument

Once your group has finished collecting and analyzing your data, your group will need to develop an initial argument. Your argument must include a claim, evidence to support your claim, and a justification of the evidence. The *claim* is your group's answer to the guiding question. The *evidence* is an analysis and interpretation of your data. Finally, the *justification* of the evidence is why your group thinks the evidence matters. The justification of the evidence is important because scientists can use different kinds of evidence to support their claims. Your group will create your initial argument on a whiteboard. Your whiteboard should include all the information shown in Figure L23.2.

FIGURE L23.2

Argument presentation on a whiteboard



Argumentation Session

The argumentation session allows all of the groups to share their arguments. One or two members of each group will stay at the lab station to share that group's argument, while the other members of the group go to the other lab stations to listen to and critique the other arguments. This is similar to what scientists do when they propose, support, evaluate, and refine new ideas during a poster session at a conference. If you are presenting your group's argument, your goal is to share your ideas and answer questions. You should also keep a record of the critiques and suggestions made by your classmates so you can use this feedback to make your initial argument stronger. You can keep track of specific critiques and suggestions for improvement that your classmates mention in the space below.

Critiques about our initial argument and suggestions for improvement:

If you are critiquing your classmates' arguments, your goal is to look for mistakes in their arguments and offer suggestions for improvement so these mistakes can be fixed. You should look for ways to make your initial argument stronger by looking for things that the other groups did well. You can keep track of interesting ideas that you see and hear during the argumentation in the space below. You can also use this space to keep track of any questions that you will need to discuss with your team.

Interesting ideas from other groups or questions to take back to my group:

Once the argumentation session is complete, you will have a chance to meet with your group and revise your initial argument. Your group might need to gather more data or design a way to test one or more alternative claims as part of this process. Remember, your goal at this stage of the investigation is to develop the best argument possible.

Report

Once you have completed your research, you will need to prepare an *investigation report* that consists of three sections. Each section should provide an answer to the following questions:

1. What question were you trying to answer and why?
2. What did you do to answer your question and why?
3. What is your argument?

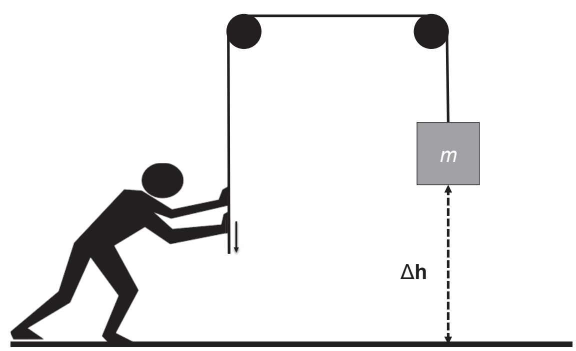
Your report should answer these questions in two pages or less. This report must be typed, and any diagrams, figures, or tables should be embedded into the document. Be sure to write in a persuasive style; you are trying to convince others that your claim is acceptable or valid!

Checkout Questions

Lab 23. Power: Which Toy Car Has the Engine With the Greatest Horsepower?

1. How do the law of conservation of energy and the work-energy theorem help engineers determine the horsepower of a motor?

2. In the figure at right, a person uses a pulley to lift a box off the ground. Assuming that the person lifts the box of mass *m* with a constant velocity **v** and lifts the box a height of Δ**h** in *t* seconds, create a mathematical expression for the rate at which the person does work on the box.



3. Scientists need to be creative and have a good imagination.

    a. I agree with this statement.
    b. I disagree with this statement.

    Explain your answer, using an example from your investigation about the horsepower of a toy car.

4. A scientist must first make an observation before he or she can make an inference.

    a. I agree with this statement.
    b. I disagree with this statement.

    Explain your answer, using an example from your investigation about the horsepower of a toy car.

5. Scientists often need to define a system under study during an investigation. Explain why it is useful to define a system under study during an investigation, using an example from your investigation about the horsepower of a toy car.

6. Scientists often need to track how matter moves into and within a system. Explain why this is important, using an example from your investigation about the horsepower of a toy car.

SECTION 8
Appendixes

APPENDIX 1

Standards Alignment Matrixes

Standards Matrix A: Alignment of the Argument-Driven Inquiry Lab Investigations With the Scientific Practices, Crosscutting Concepts, and Core Ideas in *A Framework for K–12 Science Education* (NRC 2012)

Aspect of the NRC *Framework*	Lab Investigation																						
	Lab 1. Acceleration and Velocity	Lab 2. Acceleration and Gravity	Lab 3. Projectile Motion	Lab 4. The Coriolis Effect	Lab 5. Force, Mass, and Acceleration	Lab 6. Forces on a Pulley	Lab 7. Forces on an Incline	Lab 8. Friction	Lab 9. Falling Objects and Air Resistance	Lab 10. Rotational Motion	Lab 11. Circular Motion	Lab 12. Torque and Rotation	Lab 13. Simple Harmonic Motion and Pendulums	Lab 14. Simple Harmonic Motion and Springs	Lab 15. Simple Harmonic Motion and Rubber Bands	Lab 16. Linear Momentum and Collisions	Lab 17. Impulse and Momentum	Lab 18. Elastic and Inelastic Collisions	Lab 19. Impulse and Materials	Lab 20. Kinetic and Potential Energy	Lab 21. Conservation of Energy and Pendulums	Lab 22. Conservation of Energy and Wind Turbines	Lab 23. Power
Scientific practices																							
Asking Questions and Defining Problems	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Developing and Using Models				■		■		■	■					■	■		■			■		■	■
Planning and Carrying Out Investigations	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Analyzing and Interpreting Data	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Using Mathematics and Computational Thinking	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Constructing Explanations and Designing Solutions	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Engaging in Argument From Evidence	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Key: ■ = strong alignment; □ = moderate alignment.

Aspect of the NRC *Framework*	Lab 1. Acceleration and Velocity	Lab 2. Acceleration and Gravity	Lab 3. Projectile Motion	Lab 4. The Coriolis Effect	Lab 5. Force, Mass, and Acceleration	Lab 6. Forces on a Pulley	Lab 7. Forces on an Incline	Lab 8. Friction	Lab 9. Falling Objects and Air Resistance	Lab 10. Rotational Motion	Lab 11. Circular Motion	Lab 12. Torque and Rotation	Lab 13. Simple Harmonic Motion and Pendulums	Lab 14. Simple Harmonic Motion and Springs	Lab 15. Simple Harmonic Motion and Rubber Bands	Lab 16. Linear Momentum and Collisions	Lab 17. Impulse and Momentum	Lab 18. Elastic and Inelastic Collisions	Lab 19. Impulse and Materials	Lab 20. Kinetic and Potential Energy	Lab 21. Conservation of Energy and Pendulums	Lab 22. Conservation of Energy and Wind Turbines	Lab 23. Power
Obtaining, Evaluating, and Communicating Information	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Crosscutting concepts																							
Patterns	■	■	■				■			■			■	■							■		
Cause and Effect: Mechanism and Explanation			■		■								■								■		
Scale, Proportion, and Quantity	■			■	■							■				■	■		■				
Systems and System Models				■		■		■	■		■	■		■	■			■		■		■	■
Energy and Matter: Flows, Cycles, and Conservation																■	■	■		■	■	■	■
Structure and Function						■	■	■	■	■			■						■			■	
Stability and Change		■				■					■			■	■								
Core ideas																							
PS2: Motion and Stability: Forces and Interactions	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
PS3: Energy																				■	■	■	■

Key: ■ = strong alignment; □ = moderate alignment.

Standards Matrix B: Alignment of the Argument-Driven Inquiry Lab Investigations With the Nature of Scientific Knowledge (NOSK) and the Nature of Scientific Inquiry (NOSI) Concepts*

NOSK and NOSI concepts	Lab 1. Acceleration and Velocity	Lab 2. Acceleration and Gravity	Lab 3. Projectile Motion	Lab 4. The Coriolis Effect	Lab 5. Force, Mass, and Acceleration	Lab 6. Forces on a Pulley	Lab 7. Forces on an Incline	Lab 8. Friction	Lab 9. Falling Objects and Air Resistance	Lab 10. Rotational Motion	Lab 11. Circular Motion	Lab 12. Torque and Rotation	Lab 13. Simple Harmonic Motion and Pendulums	Lab 14. Simple Harmonic Motion and Springs	Lab 15. Simple Harmonic Motion and Rubber Bands	Lab 16. Linear Momentum and Collisions	Lab 17. Impulse and Momentum	Lab 18. Elastic and Inelastic Collisions	Lab 19. Impulse and Materials	Lab 20. Kinetic and Potential Energy	Lab 21. Conservation of Energy and Pendulums	Lab 22. Conservation of Energy and Wind Turbines	Lab 23. Power
NOSK																							
The difference between observations and inferences in science	■		■			■	■			■						■					■		■
How scientific knowledge changes over time					■															■	■	■	
The difference between laws and theories in science		■			■						■						■	■		■			
The difference between data and evidence in science		■		■							■	■	■				■	■					
NOSI																							
How the culture of science, societal needs, and current events influence the work of scientists						■		■	■						■	■			■			■	
How scientists use different methods to answer different types of questions							■	■						■									
The role of imagination and creativity in science				■					■	■		■		■	■								■
The nature and role of experiments in science	■		■										■						■				

Key: ■ = strong alignment; □ = moderate alignment.

*The NOSK/NOSI concepts listed in this matrix are based on the work of Abd-El-Khalick and Lederman 2000; Akerson, Abd-El-Khalick, and Lederman 2000; Lederman et al. 2002, 2014; NGSS Lead States 2013 (see Appendix H, "Understanding the Scientific Enterprise: The Nature of Science in the *Next Generation Science Standards*"); and Schwartz, Lederman, and Crawford 2004.

Standards Matrix C: Alignment of the Argument-Driven Inquiry Lab Investigations With the *NGSS* (NGSS Lead States 2013) Performance Expectations for High School Physical Science

	Lab Investigation																						
***NGSS* performance expectation**	Lab 1. Acceleration and Velocity	Lab 2. Acceleration and Gravity	Lab 3. Projectile Motion	Lab 4. The Coriolis Effect	Lab 5. Force, Mass, and Acceleration	Lab 6. Forces on a Pulley	Lab 7. Forces on an Incline	Lab 8. Friction	Lab 9. Falling Objects and Air Resistance	Lab 10. Rotational Motion	Lab 11. Circular Motion	Lab 12. Torque and Rotation	Lab 13. Simple Harmonic Motion and Pendulums	Lab 14. Simple Harmonic Motion and Springs	Lab 15. Simple Harmonic Motion and Rubber Bands	Lab 16. Linear Momentum and Collisions	Lab 17. Impulse and Momentum	Lab 18. Elastic and Inelastic Collisions	Lab 19. Impulse and Materials	Lab 20. Kinetic and Potential Energy	Lab 21. Conservation of Energy and Pendulums	Lab 22. Conservation of Energy and Wind Turbines	Lab 23. Power
HS-PS2-1: Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.	□	□	□		■	■	■	■	■														
HS-PS2-2: Use mathematical representations to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system.																■	■	■	■				
HS-PS2-3: Apply scientific and engineering ideas to design, evaluate, and refine a device that minimizes the force on a macroscopic object during a collision.																	□	□	■				
HS-PS2-4: Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.		□	□			□																	

Key: ■ = strong alignment; □ = moderate alignment.

	Lab Investigation																						
***NGSS* performance expectation**	Lab 1. Acceleration and Velocity	Lab 2. Acceleration and Gravity	Lab 3. Projectile Motion	Lab 4. The Coriolis Effect	Lab 5. Force, Mass, and Acceleration	Lab 6. Forces on a Pulley	Lab 7. Forces on an Incline	Lab 8. Friction	Lab 9. Falling Objects and Air Resistance	Lab 10. Rotational Motion	Lab 11. Circular Motion	Lab 12. Torque and Rotation	Lab 13. Simple Harmonic Motion and Pendulums	Lab 14. Simple Harmonic Motion and Springs	Lab 15. Simple Harmonic Motion and Rubber Bands	Lab 16. Linear Momentum and Collisions	Lab 17. Impulse and Momentum	Lab 18. Elastic and Inelastic Collisions	Lab 19. Impulse and Materials	Lab 20. Kinetic and Potential Energy	Lab 21. Conservation of Energy and Pendulums	Lab 22. Conservation of Energy and Wind Turbines	Lab 23. Power
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.																					□	□	
HS-PS3-3: Design build, and refine a device that works within given constraints to convert one form of energy into another form of energy.																						■	

Key: ■ = strong alignment; □ = moderate alignment.

Standards Matrix D: Alignment of the Argument-Driven Inquiry Lab Investigations With the Science Practices and Big Ideas in AP Physics I

	Lab Investigation																						
AP Physics I science practices and big ideas	Lab 1. Acceleration and Velocity	Lab 2. Acceleration and Gravity	Lab 3. Projectile Motion	Lab 4. The Coriolis Effect	Lab 5. Force, Mass, and Acceleration	Lab 6. Forces on a Pulley	Lab 7. Forces on an Incline	Lab 8. Friction	Lab 9. Falling Objects and Air Resistance	Lab 10. Rotational Motion	Lab 11. Circular Motion	Lab 12. Torque and Rotation	Lab 13. Simple Harmonic Motion and Pendulums	Lab 14. Simple Harmonic Motion and Springs	Lab 15. Simple Harmonic Motion and Rubber Bands	Lab 16. Linear Momentum and Collisions	Lab 17. Impulse and Momentum	Lab 18. Elastic and Inelastic Collisions	Lab 19. Impulse and Materials	Lab 20. Kinetic and Potential Energy	Lab 21. Conservation of Energy and Pendulums	Lab 22. Conservation of Energy and Wind Turbines	Lab 23. Power
Science practices																							
Use representations and models to communicate scientific phenomena and solve scientific problems.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Use mathematics appropriately.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Engage in scientific questioning to extend thinking or to guide investigations.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Plan and implement data collection strategies in relation to a particular scientific question.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Perform data analysis and evaluation of evidence.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Work with scientific explanations and theories.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Connect and relate knowledge across various scales, concepts, and representations in and across domains.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Key: ■ = strong alignment; □ = moderate alignment.

AP Physics I science practices and big ideas	Lab 1. Acceleration and Velocity	Lab 2. Acceleration and Gravity	Lab 3. Projectile Motion	Lab 4. The Coriolis Effect	Lab 5. Force, Mass, and Acceleration	Lab 6. Forces on a Pulley	Lab 7. Forces on an Incline	Lab 8. Friction	Lab 9. Falling Objects and Air Resistance	Lab 10. Rotational Motion	Lab 11. Circular Motion	Lab 12. Torque and Rotation	Lab 13. Simple Harmonic Motion and Pendulums	Lab 14. Simple Harmonic Motion and Springs	Lab 15. Simple Harmonic Motion and Rubber Bands	Lab 16. Linear Momentum and Collisions	Lab 17. Impulse and Momentum	Lab 18. Elastic and Inelastic Collisions	Lab 19. Impulse and Materials	Lab 20. Kinetic and Potential Energy	Lab 21. Conservation of Energy and Pendulums	Lab 22. Conservation of Energy and Wind Turbines	Lab 23. Power
Big ideas																							
Objects and systems have properties such as mass and charge. Systems may have internal structure.					■		■	■												■	■	■	■
Fields existing in space can be used to explain interactions.		■	■			■	■		■				■		■								
The interactions of an object with other objects can be described by forces.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Interactions between systems can result in changes in those systems.	■	■		■	■			■	■	■	■	■		■		■	■	■	■			■	■
Changes that occur as a result of interactions are constrained by conservation laws.																■	■	■	■	■	■	■	■

Key: ■ = strong alignment; □ = moderate alignment.

Standards Matrix E: Alignment of the Argument-Driven Inquiry Lab Investigations With the Course Content and Science Practices and Skills in AP Physics C: Mechanics

	Lab Investigation																						
AP Physics C: Mechanics content areas and laboratory objectives	Lab 1. Acceleration and Velocity	Lab 2. Acceleration and Gravity	Lab 3. Projectile Motion	Lab 4. The Coriolis Effect	Lab 5. Force, Mass, and Acceleration	Lab 6. Forces on a Pulley	Lab 7. Forces on an Incline	Lab 8. Friction	Lab 9. Falling Objects and Air Resistance	Lab 10. Rotational Motion	Lab 11. Circular Motion	Lab 12. Torque and Rotation	Lab 13. Simple Harmonic Motion and Pendulums	Lab 14. Simple Harmonic Motion and Springs	Lab 15. Simple Harmonic Motion and Rubber Bands	Lab 16. Linear Momentum and Collisions	Lab 17. Impulse and Momentum	Lab 18. Elastic and Inelastic Collisions	Lab 19. Impulse and Materials	Lab 20. Kinetic and Potential Energy	Lab 21. Conservation of Energy and Pendulums	Lab 22. Conservation of Energy and Wind Turbines	Lab 23. Power
Content areas																							
Kinematics	■	■	■	■																			
Newton's laws of motion					■	■	■	■	■														
Work, energy, and power																				■	■	■	■
Systems of particles and linear momentum																■	■	■	■				
Circular motion and rotation										■	■	■											
Oscillations and gravitation													■	■	■								
Laboratory objectives																							
Design experiments	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Observe and measure real phenomena	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Analyze data	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Analyze error	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Communicate results	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Key: ■ = strong alignment; □ = moderate alignment

Standards Matrix F: Alignment of the Argument-Driven Inquiry Lab Investigations With the *Common Core State Standards* for English Language Arts (*CCSS ELA*; NGAC and CCSSO 2010)

	Lab Investigation																						
CCSS ELA	Lab 1. Acceleration and Velocity	Lab 2. Acceleration and Gravity	Lab 3. Projectile Motion	Lab 4. The Coriolis Effect	Lab 5. Force, Mass, and Acceleration	Lab 6. Forces on a Pulley	Lab 7. Forces on an Incline	Lab 8. Friction	Lab 9. Falling Objects and Air Resistance	Lab 10. Rotational Motion	Lab 11. Circular Motion	Lab 12. Torque and Rotation	Lab 13. Simple Harmonic Motion and Pendulums	Lab 14. Simple Harmonic Motion and Springs	Lab 15. Simple Harmonic Motion and Rubber Bands	Lab 16. Linear Momentum and Collisions	Lab 17. Impulse and Momentum	Lab 18. Elastic and Inelastic Collisions	Lab 19. Impulse and Materials	Lab 20. Kinetic and Potential Energy	Lab 21. Conservation of Energy and Pendulums	Lab 22. Conservation of Energy and Wind Turbines	Lab 23. Power
Reading																							
Key ideas and details	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Craft and structure	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Integration of knowledge and ideas	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Writing																							
Text types and purposes	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Production and distribution of writing	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Research to build and present knowledge	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Range of writing	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Speaking and listening																							
Comprehension and collaboration	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Presentation of knowledge and ideas	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Key: ■ = strong alignment; □ = moderate alignment.

Standards Matrix G: Alignment of the Argument-Driven Inquiry Lab Investigations With the *Common Core State Standards* for Mathematics (*CCSS Mathematics;* NGAC and CCSSO 2010)

	Lab Investigation																						
CCSS Mathematics	Lab 1. Acceleration and Velocity	Lab 2. Acceleration and Gravity	Lab 3. Projectile Motion	Lab 4. The Coriolis Effect	Lab 5. Force, Mass, and Acceleration	Lab 6. Forces on a Pulley	Lab 7. Forces on an Incline	Lab 8. Friction	Lab 9. Falling Objects and Air Resistance	Lab 10. Rotational Motion	Lab 11. Circular Motion	Lab 12. Torque and Rotation	Lab 13. Simple Harmonic Motion and Pendulums	Lab 14. Simple Harmonic Motion and Springs	Lab 15. Simple Harmonic Motion and Rubber Bands	Lab 16. Linear Momentum and Collisions	Lab 17. Impulse and Momentum	Lab 18. Elastic and Inelastic Collisions	Lab 19. Impulse and Materials	Lab 20. Kinetic and Potential Energy	Lab 21. Conservation of Energy and Pendulums	Lab 22. Conservation of Energy and Wind Turbines	Lab 23. Power
Mathematical practices																							
Make sense of problems and persevere in solving them	■	■	■		■		■		■					■	■							■	
Reason abstractly and quantitatively	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Construct viable arguments and critique the reasoning of others	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Model with mathematics	■		■		■		■		■					■	■							■	
Use appropriate tools strategically	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Attend to precision	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Look for and make use of structure			■		■		■		■					■	■							■	
Look for and express regularity in repeated reasoning	■	■	■		■		■		■					■	■							■	
Number and quantity																							
Extend the properties of exponents to rational exponents																							
Use properties of rational and irrational numbers																							
Reason quantitatively and use units to solve problems	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Perform arithmetic operations with complex numbers																							

Key: ■ = strong alignment; □ = moderate alignment.

	Lab Investigation																						
CCSS Mathematics	Lab 1. Acceleration and Velocity	Lab 2. Acceleration and Gravity	Lab 3. Projectile Motion	Lab 4. The Coriolis Effect	Lab 5. Force, Mass, and Acceleration	Lab 6. Forces on a Pulley	Lab 7. Forces on an Incline	Lab 8. Friction	Lab 9. Falling Objects and Air Resistance	Lab 10. Rotational Motion	Lab 11. Circular Motion	Lab 12. Torque and Rotation	Lab 13. Simple Harmonic Motion and Pendulums	Lab 14. Simple Harmonic Motion and Springs	Lab 15. Simple Harmonic Motion and Rubber Bands	Lab 16. Linear Momentum and Collisions	Lab 17. Impulse and Momentum	Lab 18. Elastic and Inelastic Collisions	Lab 19. Impulse and Materials	Lab 20. Kinetic and Potential Energy	Lab 21. Conservation of Energy and Pendulums	Lab 22. Conservation of Energy and Wind Turbines	Lab 23. Power
Number and quantity *(continued)*																							
Represent complex numbers and their operations on the complex plane																							
Use complex numbers in polynomial identities and equations																							
Represent and model with vector quantities	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Perform operations on vectors	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Perform operations on matrices and use matrices in applications																							
Algebra																							
Interpret the structure of expressions	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Write expressions in equivalent forms to solve problems					■		■																
Perform arithmetic operations on polynomials																							
Understand the relationship between zeros and factors of polynomials																							
Use polynomial identities to solve problems																							
Rewrite rational functions																							
Create equations that describe numbers or relationships			■		■		■	■	■					■						■		■	

Key: ■ = strong alignment; □ = moderate alignment.

CCSS Mathematics	Lab 1. Acceleration and Velocity	Lab 2. Acceleration and Gravity	Lab 3. Projectile Motion	Lab 4. The Coriolis Effect	Lab 5. Force, Mass, and Acceleration	Lab 6. Forces on a Pulley	Lab 7. Forces on an Incline	Lab 8. Friction	Lab 9. Falling Objects and Air Resistance	Lab 10. Rotational Motion	Lab 11. Circular Motion	Lab 12. Torque and Rotation	Lab 13. Simple Harmonic Motion and Pendulums	Lab 14. Simple Harmonic Motion and Springs	Lab 15. Simple Harmonic Motion and Rubber Bands	Lab 16. Linear Momentum and Collisions	Lab 17. Impulse and Momentum	Lab 18. Elastic and Inelastic Collisions	Lab 19. Impulse and Materials	Lab 20. Kinetic and Potential Energy	Lab 21. Conservation of Energy and Pendulums	Lab 22. Conservation of Energy and Wind Turbines	Lab 23. Power
Algebra *(continued)*																							
Understand solving equations as a process of reasoning and explain the reasoning	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Solve equations and inequalities in one variable	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Solve systems of equations																							
Represent and solve equations and inequalities graphically	■	■	■		■	■	■	■	■	■				■	■	■	■	■	■	■	■	■	■
Functions																							
Understand the concept of a function and use function notation	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■
Interpret functions that arise in applications in terms of the context	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■
Analyze functions using different representations	■	■	■		■		■		■					■	■	■	■	■	■	■	■	■	■
Build a function that models a relationship between two quantities			■		■		■		■					■						■		■	
Build new functions from existing functions																							
Construct and compare linear and exponential models and solve problems	■		■		■		■		■					■								■	
Interpret expressions for functions in terms of the situation they model	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Lab Investigation

Key: ■ = strong alignment; □ = moderate alignment.

	Lab Investigation																						
CCSS Mathematics	Lab 1. Acceleration and Velocity	Lab 2. Acceleration and Gravity	Lab 3. Projectile Motion	Lab 4. The Coriolis Effect	Lab 5. Force, Mass, and Acceleration	Lab 6. Forces on a Pulley	Lab 7. Forces on an Incline	Lab 8. Friction	Lab 9. Falling Objects and Air Resistance	Lab 10. Rotational Motion	Lab 11. Circular Motion	Lab 12. Torque and Rotation	Lab 13. Simple Harmonic Motion and Pendulums	Lab 14. Simple Harmonic Motion and Springs	Lab 15. Simple Harmonic Motion and Rubber Bands	Lab 16. Linear Momentum and Collisions	Lab 17. Impulse and Momentum	Lab 18. Elastic and Inelastic Collisions	Lab 19. Impulse and Materials	Lab 20. Kinetic and Potential Energy	Lab 21. Conservation of Energy and Pendulums	Lab 22. Conservation of Energy and Wind Turbines	Lab 23. Power
Functions *(continued)*																							
Extend the domain of trigonometric functions using the unit circle														■									
Model periodic phenomena with trigonometric functions														■									
Prove and apply trigonometric identities														■									
Statistics and probability																							
Summarize, represent, and interpret data on a single count or measurement variable																							
Summarize, represent, and interpret data on two categorical and quantitative variables	■	■	■		■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■
Interpret linear models	■		■		■	■	■		■						■							■	
Understand and evaluate random processes underlying statistical experiments		■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Make inferences and justify conclusions from sample surveys, experiments, and observational studies	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Understand independence and conditional probability and use them to interpret data																							

Key: ■ = strong alignment; □ = moderate alignment.

	Lab Investigation																						
CCSS Mathematics	Lab 1. Acceleration and Velocity	Lab 2. Acceleration and Gravity	Lab 3. Projectile Motion	Lab 4. The Coriolis Effect	Lab 5. Force, Mass, and Acceleration	Lab 6. Forces on a Pulley	Lab 7. Forces on an Incline	Lab 8. Friction	Lab 9. Falling Objects and Air Resistance	Lab 10. Rotational Motion	Lab 11. Circular Motion	Lab 12. Torque and Rotation	Lab 13. Simple Harmonic Motion and Pendulums	Lab 14. Simple Harmonic Motion and Springs	Lab 15. Simple Harmonic Motion and Rubber Bands	Lab 16. Linear Momentum and Collisions	Lab 17. Impulse and Momentum	Lab 18. Elastic and Inelastic Collisions	Lab 19. Impulse and Materials	Lab 20. Kinetic and Potential Energy	Lab 21. Conservation of Energy and Pendulums	Lab 22. Conservation of Energy and Wind Turbines	Lab 23. Power
Statistics and probability *(continued)*																							
Use the rules of probability to compute probabilities of compound events in a uniform probability model																							
Calculate expected values and use them to solve problems																							
Use probability to evaluate outcomes of decisions																							

Key: ■ = strong alignment; □ = moderate alignment.

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APPENDIX 2

OVERVIEW OF THE *NGSS* CROSSCUTTING CONCEPTS

Patterns

Scientists look for patterns in nature and attempt to understand the underlying cause of these patterns. Scientists, for example, often collect data and then look for patterns to identify a relationship between two variables, a trend over time, or a difference between groups.

Cause and Effect: Mechanism and Explanation

Natural phenomena have causes, and uncovering causal relationships (e.g., how changes in x affect y) is a major activity of science.

Scale, Proportion, and Quantity

Students need to understand that it is critical for scientists to be able to recognize what is relevant at different sizes, times, and scales. Scientists must also be able to recognize proportional relationships between categories, groups, or quantities. In physics, quantity takes on additional importance as physicists differentiate between vector quantities (quantities with magnitude and direction) and scalar quantities (quantities with only magnitude).

Systems and System Models

Students need to understand that defining a system under study and making a model of it are tools for developing a better understanding of natural phenomena in science.

Energy and Matter: Flows, Cycles, and Conservation

Students should realize that in science it is important to track how energy and matter move into, out of, and within systems.

Structure and Function

In nature, the way an object or a material is structured or shaped determines how it functions and places limits on what it can and cannot do.

Stability and Change

It is critical to understand what makes a system stable or unstable and what controls rates of change in system.

OVERVIEW OF NATURE OF SCIENTIFIC KNOWLEDGE AND SCIENTIFIC INQUIRY CONCEPTS

Nature of Scientific Knowledge Concepts

The difference between observations and inferences in science

An *observation* is a descriptive statement about a natural phenomenon, whereas an *inference* is an interpretation of an observation. Students should also understand that current scientific knowledge and the perspectives of individual scientists guide both observations and inferences. Thus, different scientists can have different but equally valid interpretations of the same observations due to differences in their perspectives and background knowledge.

How scientific knowledge changes over time

A person can have confidence in the validity of scientific knowledge but must also accept that scientific knowledge may be abandoned or modified in light of new evidence or because existing evidence has been reconceptualized by scientists. There are many examples in the history of science of both *evolutionary changes* (i.e., the slow or gradual refinement of ideas) and *revolutionary changes* (i.e., the rapid abandonment of a well-established idea) in scientific knowledge.

The difference between laws and theories in science

A *scientific law* describes the behavior of a natural phenomenon or a generalized relationship under certain conditions; a *scientific theory* is a well-substantiated explanation of some aspect of the natural world. Theories do not become laws even with additional evidence; they explain laws. However, not all scientific laws have an accompanying explanatory theory. It is also important for students to understand that scientists do not discover laws or theories; the scientific community develops them over time.

The difference between data and evidence in science

Data are measurements, observations, and findings from other studies that are collected as part of an investigation. *Evidence,* in contrast, is analyzed data and an interpretation of the analysis.

Nature of Scientific Inquiry Concepts

How the culture of science, societal needs, and current events influence the work of scientists

Scientists share a set of values, norms, and commitments that shape what counts as knowing, how to represent or communicate information, and how to interact with other scientists. The culture of science affects who gets to do science, what scientists choose to investigate, how investigations are conducted, how research findings are interpreted, and what people see as implications. People also view some research as being more important than other research because of cultural values and current events.

How scientists use different methods to answer different types of questions

Examples of methods include experiments, systematic observations of a phenomenon, literature reviews, and analysis of existing data sets; the choice of method depends on the objectives of the research. There is no universal step-by step scientific method that all scientists follow; rather, different scientific disciplines (e.g., chemistry vs. physics) and fields within a discipline (e.g., organic vs. physical chemistry) use different types of methods, use different core theories, and rely on different standards to develop scientific knowledge.

The role of imagination and creativity in science

Students should learn that developing explanations for, or models of, natural phenomena and then figuring out how these explanations or models can be put to the test of reality is as creative as writing poetry, composing music, or designing video games. Scientists must also use their imagination and creativity to figure out new ways to test ideas and collect or analyze data.

The nature and role of experiments in science

Scientists use experiments to test the validity of a hypothesis (i.e., a tentative explanation) for an observed phenomenon. Experiments include a test and the formulation of predictions (expected results) if the test is conducted and the hypothesis is valid. The experiment is then carried out and the predictions are compared with the actual results of the experiment. If the predictions match the actual results, then the hypothesis is supported. If the actual results do not match the predicted results, then the hypothesis is not supported. A signature feature of an experiment is the control of variables to help eliminate alternative explanations for the results.

APPENDIX 3

Timeline Options for Implementing ADI Lab Investigations

Option A: 6 days (280 minutes), no homework

Day	Stage	Time
1	1: Introduce the task and the guiding question	20 minutes
	2: Design a method	30 minutes
2	2: Collect data	50 minutes
3	3: Develop an initial argument	20 minutes
	4: Argumentation session (and revise initial argument)	30 minutes
4	5: Explicit and reflective discussion	20 minutes
	6: Write investigation report (draft)	30 minutes
5	7: Double-blind peer review	50 minutes
6	8: Revise and submit the investigation report	30 minutes

Option B: 5 days (220 minutes), writing done as homework

Day	Stage	Time
1	1: Introduce the task and the guiding question	20 minutes
	2: Design a method	30 minutes
2	2: Collect data	50 minutes
3	3: Develop an initial argument	20 minutes
	4: Argumentation session (and revise initial argument)	30 minutes
4	5: Explicit and reflective discussion	20 minutes
	6: Write investigation report (draft)	Homework
5	7: Double-blind peer review	50 minutes
	8: Revise and submit the investigation report	Homework

Option C: 5 days (230 minutes), no homework

Day	Stage	Time
1	1: Introduce the task and the guiding question	20 minutes
	2: Design a method and collect data	30 minutes
2	3: Develop an initial argument	20 minutes
	4: Argumentation session (and revise initial argument)	30 minutes
3	5: Explicit and reflective discussion	20 minutes
	6: Write investigation report (draft)	30 minutes
4	7: Double-blind peer review	50 minutes
5	8: Revise and submit the investigation report	30 minutes

Option D: 4 days (170 minutes), writing done as homework

Day	Stage	Time
1	1: Introduce the task and the guiding question	20 minutes
	2: Design a method and collect data	30 minutes
2	3: Develop an initial argument	20 minutes
	4: Argumentation session (and revise initial argument)	30 minutes
3	5: Explicit and reflective discussion	20 minutes
	6: Write investigation report (draft)	Homework
4	7: Double-blind peer review	50 minutes
	8: Revise and submit the investigation report	Homework

Option E: 6 days (280 minutes), no homework

Day	Stage	Time
1	1: Introduce the task and the guiding question	20 minutes
	2: Design a method	30 minutes
2	2: Collect data	30 minutes
	3: Develop an initial argument	20 minutes
3	4: Argumentation session (and revise initial argument)	30 minutes
	5: Explicit and reflective discussion	20 minutes
4	6: Write investigation report (draft)	50 minutes
5	7: Double-blind peer review	50 minutes
6	8: Revise and submit the investigation report	30 minutes

Option F: 4 days (200 minutes), writing done as homework

Day	Stage	Time
1	1: Introduce the task and the guiding question	20 minutes
	2: Design a method	30 minutes
2	2: Collect data	30 minutes
	3: Develop an initial argument	20 minutes
3	4: Argumentation session (and revise initial argument)	30 minutes
	5: Explicit and reflective discussion	20 minutes
	6: Write investigation report (draft)	Homework
4	7: Double-blind peer review	50 minutes
	8: Revise and submit the investigation report	Homework

APPENDIX 4
Investigation Proposal Options

This appendix presents six investigation proposals (long and short versions of three different types of proposals) that may be used in most labs. Investigation Proposal A is appropriate for descriptive studies, whereas Investigation Proposal B and Investigation Proposal C are appropriate for comparative or experimental studies. The development of these proposals was supported by the Institute of Education Sciences, U.S. Department of Education, through grant R305A100909 to Florida State University.

The format of investigation proposals B and C is modeled after a hypothetical deductive-reasoning guide described in *Exploring the Living World* (Lawson 1995) and modified from an investigation guide described in an article by Maguire, Myerowitz, and Sampson (2010).

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Investigation Proposal A: Descriptive Study

The Guiding Question…	
What data will you collect?	
How will you collect your data?	Your Procedure / What safety precautions will you follow?
How will you analyze your data?	

I approve of this investigation. ____________________ Instructor's Signature ________ Date

Your actual data

Your analysis of the data

The claim you will make

Investigation Proposal A: Descriptive Study (Short Form)

The Guiding Question…	
What data will you collect?	
How will you collect your data?	Your Procedure / What safety precautions will you follow?
How will you analyze your data?	
Your actual data	

I approve of this investigation. ______________________________ Instructor's Signature __________ Date

Investigation Proposal B: Comparative or Experimental Study

The Guiding Question…

Hypothesis 1

IF…

Hypothesis 2

IF…

The Test

AND…

Procedure

What data will you collect?

How will you analyze the data?

What safety precautions will you follow?

Predicted Result if hypothesis 1 is valid

THEN…

Predicted Result if hypothesis 2 is valid

THEN…

I approve of this investigation. ______________________ ____________

Instructor's Signature Date

Your actual data	AND…
Your analysis of the data	
The claim you will make	

Investigation Proposal B: Comparative or Experimental Study (Short Form)

The Guiding Question…

Hypothesis 1

IF…

Hypothesis 2

IF…

The Test

AND…

Procedure

What data will you collect?

How will you analyze the data?

What safety precautions will you follow?

Predicted Result if hypothesis 1 is valid

THEN…

Predicted Result if hypothesis 2 is valid

THEN…

The actual results

AND…

I approve of this investigation.

Instructor's Signature

Date

Investigation Proposal C: Comparative or Experimental Study

The Guiding Question…

Hypothesis 1

IF…

Hypothesis 2

IF…

Hypothesis 3

IF…

The Test

AND…

Procedure

What data will you collect?

How will you analyze the data?

What safety precautions will you follow?

Predicted Result if hypothesis 1 is valid

THEN…

Predicted Result if hypothesis 2 is valid

THEN…

Predicted Result if hypothesis 3 is valid

THEN…

I approve of this investigation. ______________________ ____________

Instructor's Signature Date

AND…

Your actual data

Your analysis of the data

The claim you will make

Investigation Proposal C: Comparative or Experimental Study (Short Form)

The Guiding Question…

Hypothesis 1

IF…

Hypothesis 2

IF…

Hypothesis 3

IF…

The Test

AND…

Procedure

What data will you collect?

How will you analyze the data?

What safety precautions will you follow?

Predicted Result if hypothesis 1 is valid

THEN…

Predicted Result if hypothesis 2 is valid

THEN…

Predicted Result if hypothesis 3 is valid

THEN…

The actual results

AND…

I approve of this investigation. ______________________ Instructor's Signature ________ Date

APPENDIX 5

Investigation Report Peer-Review Guide: High School Version

Report By: ______________________ Author: Did the reviewers do a good job? 1 2 3 4 5

ID Number — Rate the overall quality of the peer review

Reviewed By: ______________ ______________ ______________ ______________

ID Number ID Number ID Number ID Number

Section 1: Introduction and Guiding Question	Reviewer Rating			Teacher Score
1. Did the author provide enough ***background information***?	☐ No	☐ Partially	☐ Yes	0 1 2
2. Is the background information ***accurate***?	☐ No	☐ Partially	☐ Yes	0 1 2
3. Did the author ***describe the goal*** of the study?	☐ No	☐ Partially	☐ Yes	0 1 2
4. Did the author make the ***guiding question*** explicit and explain how the guiding question is related to the background information?	☐ No	☐ Partially	☐ Yes	0 1 2
Reviewers: If your group made any “No” or “Partially” marks in this section, please ***explain how the author could improve*** this part of his or her report.	**Author:** What revisions did you make in your report? Is there anything you decided to keep the same even though the reviewers suggested otherwise? Be sure to explain why.			

Section 2: Method	Reviewer Rating			Teacher Score
1. Did the author describe ***the procedure*** he or she used to gather data and then explain why he or she used this procedure?	☐ No	☐ Partially	☐ Yes	0 1 2
2. Did the author explain ***what data*** were collected (or used) during the investigation and why they were collected (or used)?	☐ No	☐ Partially	☐ Yes	0 1 2
3. Did the author describe ***how he or she analyzed the data*** and explain why the analysis helped him or her answer the guiding question?	☐ No	☐ Partially	☐ Yes	0 1 2

Section 2: Method *(continued)*	Reviewer Rating			Teacher Score
4. Did the author use the ***correct term*** to describe his or her investigation (e.g., experiment, observations, interpretation of a data set)?	☐ No	☐ Partially	☐ Yes	0 1 2
Reviewers: If your group made any "No" or "Partially" marks in this section, please ***explain how the author could improve*** this part of his or her report.	**Author:** What revisions did you make in your report? Is there anything you decided to keep the same even though the reviewers suggested otherwise? Be sure to explain why.			

Section 3: The Argument	Reviewer Rating			Teacher Score
1. Did the author provide a ***claim*** that answers the guiding question?	☐ No	☐ Partially	☐ Yes	0 1 2
2. Did the author include ***high-quality evidence*** in his/her argument?				
• Were the data collected in an appropriate manner?	☐ No	☐ Partially	☐ Yes	0 1 2
• Is the analysis of the data appropriate and free from errors?	☐ No	☐ Partially	☐ Yes	0 1 2
• Is the author's interpretation of the analysis (what it means) valid?	☐ No	☐ Partially	☐ Yes	0 1 2
3. Did the author ***present the evidence*** in an appropriate manner by				
• using a correctly formatted and labeled graph (or table);	☐ No	☐ Partially	☐ Yes	0 1 2
• including correct metric units (e.g., m/s, g, ml); and	☐ No	☐ Partially	☐ Yes	0 1 2
• referencing the graph or table in the body of the text?	☐ No	☐ Partially	☐ Yes	0 1 2
4. Is the claim ***consistent with the evidence***?	☐ No	☐ Partially	☐ Yes	0 1 2
5. Did the author include a ***justification of the evidence*** that				
• explains why the evidence is important (why it matters) and	☐ No	☐ Partially	☐ Yes	0 1 2
• defends the inclusion of the evidence with a specific science concept or by discussing his/her underlying assumptions?	☐ No	☐ Partially	☐ Yes	0 1 2
6. Is the ***justification of the evidence*** acceptable?	☐ No	☐ Partially	☐ Yes	0 1 2
7. Did the author discuss ***how well his/her claim agrees with the claims made by other groups*** and explain any disagreements?	☐ No	☐ Partially	☐ Yes	0 1 2
8. Did the author **use scientific terms correctly** (e.g., *hypothesis* vs. *prediction, data* vs. *evidence*) and **reference the evidence in an appropriate manner** (e.g., *supports* or *suggests* vs. *proves*)?	☐ No	☐ Partially	☐ Yes	0 1 2

Section 3: The Argument *(continued)*	Reviewer Rating	Teacher Score
Reviewers: If your group made any "No" or "Partially" marks in this section, please ***explain how the author could improve*** this part of his or her report.	**Author:** What revisions did you make in your report? Is there anything you decided to keep the same even though the reviewers suggested otherwise? Be sure to explain why.	

Mechanics	Reviewer Rating			Teacher Score
1. ***Organization:*** Is each section easy to follow? Do paragraphs include multiple sentences? Do paragraphs begin with a topic sentence?	☐ No	☐ Partially	☐ Yes	0 1 2
2. ***Grammar:*** Are the sentences complete? Is there proper subject-verb agreement in each sentence? Are there no run-on sentences?	☐ No	☐ Partially	☐ Yes	0 1 2
3. ***Conventions:*** Did the author use appropriate spelling, punctuation, and capitalization?	☐ No	☐ Partially	☐ Yes	0 1 2
4. ***Word Choice:*** Did the author use the appropriate word (e.g., *there* vs. *their, to* vs. *too, than* vs. *then*)?	☐ No	☐ Partially	☐ Yes	0 1 2
Teacher Comments:				

Total: __________/50

Investigation Report Peer-Review Guide: Advanced Placement Version

Report By: ______________________
ID Number

Author: Did the reviewers do a good job? 1 2 3 4 5
Rate the overall quality of the peer review

Reviewed By: ______________ ______________ ______________ ______________
ID Number ID Number ID Number ID Number

Section 1: Introduction and Guiding Question	Reviewer Rating			Teacher Score
1. Did the author provide enough ***background information***?	☐ No	☐ Partially	☐ Yes	0 1 2
2. Is the background information ***accurate***?	☐ No	☐ Partially	☐ Yes	0 1 2
3. Did the author ***describe the goal*** of the study?	☐ No	☐ Partially	☐ Yes	0 1 2
4. Did the author make the ***guiding question*** explicit and explain how the guiding question is related to the background information?	☐ No	☐ Partially	☐ Yes	0 1 2
Reviewers: If your group made any "No" or "Partially" marks in this section, please ***explain how the author could improve*** this part of his or her report.	**Author:** What revisions did you make in your report? Is there anything you decided to keep the same even though the reviewers suggested otherwise? Be sure to explain why.			

Section 2: Method	Reviewer Rating			Teacher Score
1. Did the author describe ***the procedure*** he or she used to gather data and then explain why he or she used this procedure?	☐ No	☐ Partially	☐ Yes	0 1 2
2. Did the author explain ***what data*** were collected (or used) during the investigation and why they were collected (or used)?	☐ No	☐ Partially	☐ Yes	0 1 2
3. Did the author describe ***how he or she analyzed the data*** and explain why the analysis helped him or her answer the guiding question?	☐ No	☐ Partially	☐ Yes	0 1 2

Section 2: Method *(continued)*	**Reviewer Rating**			**Teacher Score**
4. Did the author use the ***correct term*** to describe his or her investigation (e.g., experiment, observations, interpretation of a data set)?	☐ No	☐ Partially	☐ Yes	0 1 2
Reviewers: If your group made any "No" or "Partially" marks in this section, please ***explain how the author could improve*** this part of his or her report.	**Author:** What revisions did you make in your report? Is there anything you decided to keep the same even though the reviewers suggested otherwise? Be sure to explain why.			

Section 3: The Argument	**Reviewer Rating**			**Teacher Score**
1. Did the author provide a ***claim*** that answers the guiding question?	☐ No	☐ Partially	☐ Yes	0 1 2
2. Did the author include ***high-quality evidence*** in his/her argument?				
• Were the data collected in an appropriate manner?	☐ No	☐ Partially	☐ Yes	0 1 2
• Is the analysis of the data appropriate and free from errors?	☐ No	☐ Partially	☐ Yes	0 1 2
• Is the author's interpretation of the analysis (what it means) valid?	☐ No	☐ Partially	☐ Yes	0 1 2
3. Did the author ***present the evidence*** in an appropriate manner by				
• using a correctly formatted and labeled graph (or table);	☐ No	☐ Partially	☐ Yes	0 1 2
• including correct metric units (e.g., m/s, g, ml); and	☐ No	☐ Partially	☐ Yes	0 1 2
• referencing the graph or table in the body of the text?	☐ No	☐ Partially	☐ Yes	0 1 2
4. Is the claim ***consistent with the evidence***?	☐ No	☐ Partially	☐ Yes	0 1 2
5. Did the author include a ***justification of the evidence*** that				
• explains why the evidence is important (why it matters) and	☐ No	☐ Partially	☐ Yes	0 1 2
• defends the inclusion of the evidence with a specific science concept or by discussing his/her underlying assumptions?	☐ No	☐ Partially	☐ Yes	0 1 2
6. Is the ***justification of the evidence*** acceptable?	☐ No	☐ Partially	☐ Yes	0 1 2
7. Did the author discuss ***how well his/her claim agrees with the claims made by other groups*** and explain any disagreements?	☐ No	☐ Partially	☐ Yes	0 1 2
8. Did the author **use scientific terms correctly** (e.g., *hypothesis* vs. *prediction, data* vs. *evidence*) and **reference the evidence in an appropriate manner** (e.g., *supports* or *suggests* vs. *proves*)?	☐ No	☐ Partially	☐ Yes	0 1 2

Section 3: The Argument *(continued)*	
Reviewers: If your group made any "No" or "Partially" marks in this section, please ***explain how the author could improve*** this part of his or her report.	**Author:** What revisions did you make in your report? Is there anything you decided to keep the same even though the reviewers suggested otherwise? Be sure to explain why.

Section 4: Limitations and Implications	Reviewer Rating			Teacher Score
1. Did the author discuss the ***limitations of the study*** and what he or she could have done in order to ***increase the rigor*** of the investigation?	☐ No	☐ Partially	☐ Yes	0 1 2
2. Did the author discuss ***sources of error*** that were unavoidable in the collection of the data?	☐ No	☐ Partially	☐ Yes	0 1 2
3. Did the author discuss ***new questions*** to explore?	☐ No	☐ Partially	☐ Yes	0 1 2
Reviewers: If your group made any "No" or "Partially" marks in this section, please ***explain how the author could improve*** this part of his or her report.	**Author:** What revisions did you make in your report? Is there anything you decided to keep the same even though the reviewers suggested otherwise? Be sure to explain why.			

Mechanics	Reviewer Rating			Teacher Score
1. ***Organization:*** Is each section easy to follow? Do paragraphs include multiple sentences? Do paragraphs begin with a topic sentence?	☐ No	☐ Partially	☐ Yes	0 1 2
2. ***Grammar:*** Are the sentences complete? Is there proper subject-verb agreement in each sentence? Are there no run-on sentences?	☐ No	☐ Partially	☐ Yes	0 1 2
3. ***Conventions:*** Did the author use appropriate spelling, punctuation, and capitalization?	☐ No	☐ Partially	☐ Yes	0 1 2
4. ***Word Choice:*** Did the author use the appropriate word (e.g., *there* vs. *their, to* vs. *too, than* vs. *then*)?	☐ No	☐ Partially	☐ Yes	0 1 2
Teacher Comments:				

Total: __________/56

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Lab 4

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